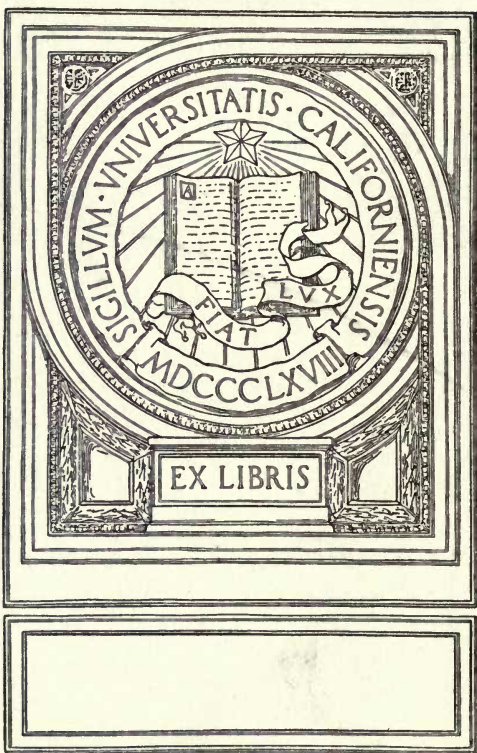


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# STEEL

## AND ITS HEAT TREATMENT

BY  
**DENISON K. BULLENS**  
*Consulting Metallurgist*

*FIRST EDITION*

FIRST THOUSAND



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IN MEMORY OF MY FATHER

Albert Nelson Bullens

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## PREFACE

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MODERN Heat Treatment should be considered as an art or trade, since it certainly requires knowledge, skill and judgment for its proper performance. These, in turn, necessitate at least some knowledge of heat, of steel, and of the effect of heat upon steel. And all three factors are linked together by the "human element." The author has therefore endeavored to bring together the theoretical and practical sides of the general subject of steel and its heat treatment in such a manner as will, he hopes, be understandable by that "human element."

It has been the author's attempt to make the chapters dealing with the heating problem more of a "heat talk" than of a "furnace talk"; of heat application rather than details of construction; of the importance of the human element and scientific efficiency rather than the elimination of the human element through scientific management; and finally, of viewing the heating problem as an engineering proposition, adapting each fuel to proper furnace design and operation to meet the requirements of the problem in hand, and by so doing aim for the adoption of the standard heating unit in terms of finished product—"the cost of a unit of quantity of given quality."

He has attempted to make as practical as possible those chapters relating to steel and the effect of heat upon steel. Theories have been advanced only so far as has been thought necessary for a clear understanding of principles. Wherever possible, illustrations in the form of photomicrographs and charts have been given. The data given under the various types of heat-treated steels have been checked as far as possible and every effort has been made to be correct.



To the many friends who have aided him in the preparation of this book the author would express his sincere appreciation. Effort has been made to give due credit for cuts and data at the proper place, and for such as may not have been made, acknowledgment is hereby rendered.

DENISON K. BULLENS.

PHILADELPHIA,  
October 1, 1915.

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# STEEL AND ITS HEAT TREATMENT

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## CHAPTER I

### THE TESTING OF STEEL

**Growth of Heat Treatment.**—Probably no one division in the metallurgy of steel has taken such wonderful strides in recent years as has the art of heat treatment. Twenty years ago the scientific knowledge and technical application of heat treatment were but very limited. Such as it was, it usually consisted in “heating to a red heat” for annealing, or perhaps the instructions called for “harden at a bright red and temper to a straw color.” Then it was an art guarded with much secrecy and confined for the most part to makers of tools and a certain few specialties.

Practically all alloy steels require treatment of one sort or another. In the “natural” state very few steels present their full value, so that heat treatment is not only advisable but often mandatory.

**Necessity for Heat Treatment.**—Take for example the steels used in the automobile industry. The frame requires resistance to vibratory stresses occasioned by rough roads, as well as strength and toughness. Rear axles must have great torsional resistance; front axles must withstand vibrations. The steering parts must be strong, tough and without brittleness; the springs must neither sag nor break. Crank-shafts must be able to resist impact, besides being stiff. Gears are subject to wear and must be capable of withstanding this action if a smoothly running transmission is to be had. And so each separate part might be named, all having a more or less severe duty to perform and requiring steels possessing various degrees of strength, toughness, resilience, endurance, shock-resisting and wearing qualities.

**Testing.**—These various combinations of static and dynamic strength are obtained by adjusting and correlating both the chemical

composition and heat treatment of the steel. Certain chemical components intensify the static properties of the material; others may affect the dynamic qualities. Thus by coupling with a steel of suitable chemical combination the proper heat treatment, there arises a product with physical properties most adapted for the work in hand. Similarly, having once produced a suitable article, it then remains to duplicate it. To this end all rational heat treatment must be aligned and standardization of results be obtained. In order to accomplish these specific requirements, the influence of definite chemical composition and definite treatment must be known, as will be described in later chapters. The guide to this work is frequent and constant testing, and a definite knowledge of the various components should be possessed by every heat-treatment man. Thus we may say that the purpose of practical testing is (1) to supply information as to suitable material and its qualities for different purposes, both for the manufacturer of the material and for the designer or user, and (2) to test the specified uniform quality of the material.

**Stresses and Strains.**—Testing resolves itself into a determination of the strength of the material, which in turn is measured by the application of a force and its resultant effect. The force put upon a body is termed the stress, and the deformation resulting from that force is the strain. Upon the method of applying that force depends the nature of the test. Thus we may conveniently classify such stresses under the following headings:

- A. Steady or constant loads—static stresses;
- B. Repeated static stresses and accelerated stresses—fatigue stresses;
- C. Suddenly applied loads—impact stresses;
- D. Repeated impact or vibratory stresses—dynamic stresses;
- E. Miscellaneous tests such as resistance to penetration, wear, etc.

**Tensile Strength.**—The most common test for static strength, that is, the strength of the steel under constant load and without shock or vibration, is the tensile test. Thus we may call the tensile strength the absolute strength of the metal under tension, i.e., the force actually required to pull the metal asunder. A standard test piece is gripped between the upper and lower jaws of a testing machine and the total resistance to rupture is measured. Knowing the area of the cross-section of the test piece and the load required to break

it, the strength per square unit may then be calculated. The tensile strength is usually given in pounds per square inch (American), tons per square inch (British), or kilograms per square millimeter (metric system;  $1 \text{ kg. per mm.}^2 = 1422.32 \text{ lbs. per square inch}$ ). The accuracy of the tensile test is dependent not only upon the conditions under which the test is made, such as the rate of pulling, alignment of test piece in the machine, etc., and which are more or less influenced by the human element, but also upon the metal itself. The higher the tensile strength and brittleness of the steel, the greater the possibility of error; differences of several thousand pounds per square inch are often encountered in the same piece of high-tensile, heat-treated steel, even in the absence of brittleness.

Test pieces are generally taken half way between the center and the outside of the piece, and longitudinally or "with the grain." Occasionally it is necessary to take tests transversely or "across the grain"; in this case the results will be lower than in the longitudinal test, the exact amount depending upon the composition and treatment of the steel.

The static strength increases in direct proportion to the carbon content of the steel. For the ordinary basic and acid open-hearth steels, without heat treatment, Campbell gives the following formulæ by which the tensile strength of such steels may be roughly determined. These results apply for steel "in the natural."

Acid open-hearth steel:

$$\text{Tensile strength} = 40,000 + 1000C + 1000P + x\text{Mn.}$$

Basic open hearth steel:

$$\text{Tensile strength} = 41,500 + 770C + 1000P + y\text{Mn.}$$

In these formulæ, C equals each one point (0.01 per cent.) of carbon as determined by combustion, P equals each 0.01 per cent. of phosphorus, Mn equals each 0.01 per cent. of manganese, and  $x$  and  $y$  are given in the table on page 4.

**Elastic Limit (Tension).**—The term "elastic limit" has probably been more ill-used than any other common technical testing name, with the possible exception of "hardness." Among its many definitions the two which stand out pre-eminently are (1) the least stress at which the material retains a permanent deformation or "set" after the removal of the stress; and (2) the least stress under



Percentage of Carbon.	On Acid Steel.	On Basic Steel.
	$x$ Lbs. per Sq. In.	$y$ Lbs. per Sq. In.
0.05.....	.....	110†
0.10.....	80*	130
0.15.....	120	150
0.20.....	160	170
0.25.....	200	190
0.30.....	240	210
0.35.....	280	230
0.40.....	320	250
0.45.....	360	
0.50.....	400	
0.55.....	440	
0.60.....	480	

\* Beginning only with 0.4 per cent. manganese.

† Beginning only with 0.3 per cent. manganese.

which ductile material exhibits a marked yielding—sometimes denoted as the “yield point.”

The determination of the true elastic limit should always be taken from a curve plotted, using an extensometer, from a series of careful observations, as otherwise sets caused by non-homogeneity and initial stress might be obtained which do not represent the plasticity of the material. This method of determining the elastic limit is but little used commercially, as the amount of labor involved is too great.

The yield point, or commercial elastic limit, is obtained by noting the stress at which the test piece first begins to “give” or elongate. This may be obtained by means of two prick-punch marks and observing the first signs of elongating by means of dividers held on these points; or by noting the drop of the weighing beam or halt in the load indicator (“jockey”); or by means of the general appearance of the test piece.

In its practical application the elastic limit may be called the working strength of the material, for in most cases the steel or machine part becomes useless when strained beyond its elastic limit. This is particularly true of automobile construction, in which the value of a car is dependent upon the correct adjustment and alignment of its several working parts, such as in transmissions and transmission suspensions. All tests given in this book, unless otherwise noted, refer to the commercial elastic limit or yield point.

The relation existing between the elastic limit and the tensile strength is too broad a subject for discussion here, as the varying chemical compositions and heat treatments exert such a tremendous influence; a study of the results given in following chapters will show a proportionality of 40 per cent. and upward.

**Elongation.**—The elongation is measured in per cent. of the original test section and is commonly the amount of stretch which will occur in the material when pulled apart by tension. It is usually measured in relation to an initial distance of 2 or 8 in., or 100 mm. when the metric system is used, but other specifications as used in Europe give a definite relation of original gauge-length to the thickness or diameter of the specimen.

**Reduction (or Contraction) of Area.**—The reduction of area refers to the area at the point of rupture, usually reported in per cent. reduction of the original area—that is, the original area of the test piece minus the area of the smallest cross-section after fracture; this divided by the original area is the percentage reduction of area.

**Ductility.**—The percentage elongation and percentage reduction of area are a measure of the “ductility” of the material, usually varying inversely with the tensile strength. The true measure of the ductility of the steel cannot be taken alone from either the elongation or reduction of area, as the results obtained in either case will depend in a large measure upon the size of the test piece, the method of testing, etc. Many engineers regard the reduction of area as the more reliable; this is offset by the fact that many steel specifications make no mention of the reduction of area, but particularly specify the percentage elongation. Ductility may also be defined as the amount of distortion of the material before final rupture.

**Compressive Strength.**—The compressive strength of material is its resistance to crushing. The test is generally carried out upon a small cylinder or 1-in. cube of the metal, using the same machine as for the tensile test. Care must be used to see that the line of strain passes exactly through the axis of the specimen, and that the plates above and below the piece have a greater resistance to penetration than the metal to be tested. The application of the term elastic limit is similar to that in the tensile test.

**Torsional Strength.**—As its name implies, the torsion test is used to determine the resistance to twisting. This test is very largely used to-day for automobile steel and is measured in inch-pounds with the amount of distortion given in degrees. The elastic limit is



obtained as in a tension test, using either a tropometer or an autographic attachment. The usual comparison is by calculating the shearing stress in pounds per square inch.

**Endurance.**—The computation and understanding of such static stresses as have been previously outlined are comparatively simple. The requirement to be fulfilled in designing is that the working stress shall not exceed the elastic limit of the material, whether it be in tension, compression or torsion. Numerous every-day failures, however, which cannot be accounted for by the limited information given by such tests, have forced investigators to probe more deeply into the complicated kinematic forces which seem to have such a great influence upon the “life” of the metal. It is now a well-known fact that, if a stress is applied a great number of times, i.e., repeated, each application being made before the material has had time to recover from the preceding stress, the material will eventually break even though the stress is below the elastic limit of the material. These repeated stresses upon steel cause a gradual disturbance of the structure and its component particles, which greatly weakens the material, and is called fatigue. The resistance to fatigue and its numerical test value may be termed the endurance of the steel. The stresses embodied under the heading of fatigue may be broadly classed as repeated static stresses and acceleration stresses ranging from zero to maximum or from a negative maximum to a positive maximum—alternating—stresses.

**Fatigue Stresses.**—These stresses are produced in a machine part by an external force or forces of varying strength and direction acting upon the part. When the force is produced by a continuously varying acceleration or retardation of masses taking part in the movement of the machine part, they may be conveniently termed acceleration stresses.<sup>1</sup> Typical stresses of this category are the revolving shaft stress on a loaded wheel or machine axle, the piston pressure and the acceleration pressure of the movable parts in the piston rod and crank-shaft of high-speed steam and oil engines. These perpetual stresses or so-called fatigue stresses are the essential ones in the movable parts of most high-speed machines, and a knowledge of the capacity of the material to resist them should serve as a basis for the selection of the material and design.

**Rotary Bending.**—Such static endurance tests may be carried out in a machine of the rotary bending type, such as the Wöhler or the White-Souther machines. From a study of a large number of

<sup>1</sup> J. O. Roos af Hjelmsaeter, *Int. Assoc. Test. Mat.*, 1912, Vol. II, No. 9.



experiments made on a rotary bending machine of the Wöhler design, Foos concludes that such endurance tests are not suitable as specification tests, but are of great value in the selection of material and the heat treatment for various purposes.

On the other hand, the real value of the rotary bending test as a criterion of the brittleness-fatigue endurance has been of late greatly questioned. That the results usually obtained are largely indicative of the elastic limit alone is probably more in accord with our present-day knowledge. The results from a series of tests conducted by Foos upon a Wöhler type rotary bending machine with steels of 0.11, 0.40 and 0.65 per cent. carbon, given in the following table, would tend to support the latter theory, as one would naturally expect from past experience that the 0.40 per cent. carbon steel would have a greater fatigue-resisting strength than the 0.65 carbon steel.

ROTARY BENDING TESTS, WÖHLER MACHINE

Steel.	Treatment.	Chemical.					Static Properties.			Endurance Limit.
		Carbon.	Manganese.	Phosphorus.	Sulphur.	Silicon.	Tensile Strength Lbs. per Sq. In.	Elastic Limit Lbs. per Sq. In.	Elonga- tion, Per Cent in 3.94 Ins.	Fiber Stress in Kg. giving Fracture after 1 Million Revolutions.
R	A	0.11	0.33	0.019	0.013	0.01	49,770	32,990	34.1	16
S <sub>1</sub>	A	0.40	0.51	0.027	0.011	0.20	82,760	50,770	23.8	22
S <sub>2</sub>	O.T.	0.40	0.51	0.027	0.011	0.20	109,780	70,820	15.6	28
T <sub>1</sub>	A	0.65	0.49	0.023	0.007	0.20	116,040	50,900	14.3	25
T <sub>2</sub>	O.T.	0.65	0.49	0.023	0.007	0.20	151,020	94,560	11.0	38

Treatment. "A," heated at 1560° F. for 30 minutes, and air-cooled.

"O.T.," heated at 1560° F. for 30 minutes, quenched in mineral oil, and re-heated to 1025° F.

**Suddenly Applied Loads.**—Machine parts at one time or another may be exposed to abnormal working loads such as may result from a single accidental blow or a sudden retardation of masses in motion, and which in any case cannot be supposed to be frequently repeated. Such abnormal stresses are therefore in the nature of suddenly applied loads or impact stresses, and constitute a different group from those previously discussed under static stresses. It is evident that such stresses demand that the material be able to sustain a great work of deformation for a single or a few impacts without rupture—that is,

the machine part shall sustain as little damage or deformation as possible. In general the "ductility" (elongation and reduction of area) has for a long time been used as a measure of the work of rupture. But, although such tests are of comparative value, they do not measure either the ductility under impact or the strength or resistance under impact.

**Drop Test.**—The drop test as commercially applied may be described as an aggravated bend test on a large scale. It is a relative or qualitative test only, usually made on a full-size forging, to determine roughly the homogeneity of the metal and its ductility under shock. We have arbitrarily separated this test from the "impact" tests, reserving the latter as applied to the specific measurement of the impact strength upon a more or less standardized test bar. The most common application of the drop test is that of locomotive axles, in which it is required that the axle shall stand a specified number of blows at a given height without rupture and without exceeding, as a result of the first blow, a certain deflection.

**Impact Strength.**—The impact test is used to determine the ability of the metal to withstand a suddenly applied load in the nature of an impact or shock, thus detecting brittleness or lack of toughness. This function is called *résilience* by the foreign technical world, referring to fragility or the converse of brittleness, and is stated in terms of the specific work of rupture under impact. It should not be confused with the English word "resilience," which is interpreted in this country as "springiness." This fragility is not defined by the tensile test, although an experienced steel man, from an examination of the size and aspect of the grain and other conditions of the fracture of the test piece, can usually express an opinion as to the fragility, but he cannot assess any definite value. Although the drop test specifies the fragility in a qualitative manner, it does not measure the actual resistance to rupture, and is therefore but an imperfect test. In order to overcome such objections and to arrive at a definite value, machines have been devised which break a special notched bar by a blow—the force required to rupture the metal being measured in kilogram-meters or foot-pounds. Notched test bars are used in order to localize the deformations. The blow must be delivered with sufficient velocity to bring out the desired brittleness functions. This blow or impact may be obtained by a falling weight (the Frémont machine), by a falling pendulum (the Charpy principle), or by a revolving fly-wheel bearing a releasable knife (the Guillery machine), these three representing the most



common types of impact machines in use abroad, as well as the Olsen pendulum type (using a test specimen in the form of a cantilever) in this country.

**Impact Tests.**—Frémont<sup>1</sup> recommends as the ideal conditions to be realized in the application of the impact test: (1) A minimum drop of four meters, or proportional to the impact speed; (2) the weight of the anvil block to be equal to at least forty times the weight of the tup; (3) sufficient ease and rapidity of adjustment of the machine.

On account of the many factors entering into the problem and the numerous designs of impact testing machines, the majority of the testing associations have abstained from prescribing any special type of apparatus for performing the test. The Copenhagen Congress (1909) of the International Society for Testing Materials has, however, recommended the use of a standard notched test bar of  $30 \times 30 \times 160$  mm., or a smaller bar of  $10 \times 10$  mm. cross-section when the larger size is not available. On the contrary, there are many who believe that a smaller, rectangular test bar reveals more clearly the local defects which form the nucleus of future cracks, etc.

**Use of Impact Tests.**—The fragility test has a double purpose—to point out steel which is defective, either inherently or by incorrect heat treatment; and to act as a valuable aid for the adjustment of a proper heat treatment. It is evident that steels burdened with sulphur and phosphorus, or rotten with piping and segregation, will always remain brittle whatever one may do. But ordinary, sound stock, properly treated, is nearly always non-brittle. The degree of brittleness will of course vary according to the composition, treatment and use of the different steels. The effect of heat treatment upon the impact strength is very great, so that due care should be used in so adjusting the chemical composition and treatment of the steel as to give the best combination for the work in hand. The impact test, in conjunction with other tests, gives a quick method of determining a quality the importance of which is yearly becoming more prominent scientifically; commercially, however, the impact tests are so unreliable, or vary so greatly, that they can hardly be used with any degree of accuracy.

**Fatigue Impacts.**—An impact or shock has a considerably greater effect than a stress slowly applied, and if repeated a sufficient number of times will eventually result in the rupture of the specimen. When such frequently repeated stresses are comparatively small—

<sup>1</sup>Ch. Frémont, Proc. Int. Assoc. Test. Mat., Vol. II, No. 9, 1912.



that is, are well below the elastic limit of the material—they may be termed fatigue impacts. Their measurement, as determined by the energy or amount of work they represent, is a principal component of the dynamic strength of the material. Apparatus for thus testing the material is developed upon the principle of alternating impacts. As practical examples of such stresses in commercial application there may be mentioned the stresses to which the axles of locomotives or railway cars are subjected every time the wheel passes over a rail joint, or the impact stresses sustained by different parts of a motor car when passing over bad roads, or in changing to different speeds, etc.

**Alternating Impact Machines.**—Various machines for establishing comparative numerical values for this dynamic strength have been designed, in the endeavor to produce an alternating flexure and at the same time deliver a blow or impact. This has been accomplished by applying blows to the upper part of a test piece with the aid of two pendulum balls which are made to fall alternately from opposite directions from a certain height against the test piece. Other machines have been patterned along the lines of the Upton-Lewis machine, keeping the fiber stress well within the elastic limit.

**Alternating Impact Test Results.**—The study of a great number of alternating impact tests of a comparative nature, the views of other engineers, and the study of steel parts broken in service, would lead the author to the opinion that the dynamic strength (using the term in its broadest meaning) of straight carbon steels reaches a maximum at 0.25 to 0.35 per cent. carbon, with perhaps even narrower limits of 0.25 to 0.30 per cent. carbon. Further, the maximum endurance is obtained when the steels have been properly hardened from a temperature slightly over the upper critical range and toughened at a temperature of 1200° to 1250° F. The maximum combination of static working strength, ductility, resistance to shock and vibration, and endurance probably is obtained in straight carbon steels with 0.35 to 0.45 per cent. carbon when subjected to the above treatment.

**Relation of Various Tests.**—There does not seem to be any simple relation between the elastic limit at steady tensile stress and the limit of endurance in the rotary bending test, although some engineers consider it as a “reflection of the elastic limit.” The rotary bending is undoubtedly less than the former, and according to the investigations of some engineers, the limit of endurance (rotary bending) will generally amount to about 50 to 80 per cent. of the elastic limit.

According to experiments made by Foos on straight carbon steels, the limit of endurance for rotary bending and alternating impact within the elastic limit agree fairly closely.

A high value in the work of rupture in the impact test may be considered to give comparative security in the case of occasional abnormal over-loads.

Thus, the requirements for a high-quality steel for machine parts are a high limit of endurance for the normal stresses and a high figure of rupture for the abnormal stresses. As a rule, these qualities are opposed to each other in ordinary materials, and it must rest upon experience as to which to give the preference; in parts which suffer through vibration and other fatigue stresses, it will probably be wiser to give preference to the endurance properties. It must be remembered that heat treatment and the various alloys may entirely change the different properties.

**Hardness.**—"Hardness<sup>1</sup> may be defined as the property of resisting penetration, and conversely, a hard body is one which, under suitable conditions, readily penetrates a softer material. There are, however, in metals various kinds or manifestations of hardness according to the form of stress to which the metal may be subjected. These include tensile hardness, cutting hardness, abrasion hardness, and elastic hardness; doubtless other varieties could also be recognized when the experimental conditions are modified so as to bring into operation properties of the material in addition to that of simple, or what may be conveniently called mineralogical hardness. This has been defined by Dana as 'the resistance offered by a smooth surface to abrasion.' The usual quantitative tests for hardness are static in character, but the conditions are profoundly modified when the penetrating body is moving with greater or less velocity. The resistance to the action of running water; to the effect of a sandblast; or to the result of the pounding of a heavy locomotive on a steel rail, afford examples of what might perhaps for purposes of distinction be called dynamic hardness, which is a branch of the subject which has received little quantitative examination."

**Brinell Hardness.**—The Brinell test consists in the pressing of a hardened steel ball into the surface of the object under test by means of a fixed load. The dimensions of the impression thus obtained form the basis for calculating the hardness. If the number of kilograms making up the load is divided by the spherical surface

<sup>1</sup> Thomas Turner, Inst. Journ., May, 1909.



of the impression, expressed in square millimeters, a number is obtained, expressing the pressure exerted per square millimeter of ball impression. This number is now accepted as a measure of hardness, and it is hence called the Brinell hardness number. It is generally sufficient to utilize the diameter of the ball impression itself as a measure of the hardness. In order to make tests executed at different works directly comparable, a standard ball of 10 mm. and a load of 3000 kilograms are used.

**Brinell Transference Number.**—It is a well-established fact that the Brinell hardness numbers follow very closely the tensile strength of the same types of steel, whether the steel be “in the natural,” or whether it has been subjected to some heat-treatment process. For this reason it is particularly applicable to the rapid testing of steel from which it would be impracticable to take regular tensile tests. A few comparisons between the actual tensile strength as obtained by pulling tests and the hardness number obtained from the test pieces will serve as a basis for future calculations. By obtaining such a “transference number” the probable tensile strength of the steel in question may be easily computed by multiplying the hardness number by the “transference” number. This transference number will vary with the chemical composition of the steel, and to a small extent with the manner of testing (whether with or across the grain) and between tempered and annealed steels. On the whole, however, the test is comparatively accurate for steels purchased or made under the same general chemical specification. For straight carbon steels this transference number may be said to be about 500 to 520. The Brinell method has a great advantage over the scleroscope in that it does not require an extremely smooth or polished surface for the test; the removal of scale by filing is practically the only requirement.

Many companies are standardizing their heat treatment product by taking the hardness of each piece treated, thus ensuring a close range of the desired tensile properties. On account of the influence of the size of the original section upon the physical results as obtained by the pull-test, it is much easier to determine the transference number for the specific grade of steel being treated, and then vary the toughening temperature so as to give the desired Brinell hardness number. It is the author's experience that this method is fairly accurate, and that the Brinell number will give a close approximation of the true tensile strength regardless of whether the treated bar is 1 in. or 5 ins. thick. The Brinell method is simple and com-



mercially efficient, with the exception of either very thin or highly tempered material.

For reference convenience, the relation between the diameter of the impression and the hardness number is given in the following table:

## BRINELL'S HARDNESS-NUMBERS

Diameter of Steel Ball = 10 mm.

Diameter of Ball Impression mm.	Hardness Number for a Load of 3000 Kgr.	Diameter of Ball Impression mm.	Hardness Number for a Load of 3000 Kgr.	Diameter of Ball Impression mm.	Hardness Number for a Load of 3000 Kgr.	Diameter of Ball Impression mm.	Hardness Number for a Load of 3000 Kgr.	Diameter of Ball Impression mm.	Hardness Number for a Load of 3000 Kgr.
2	946	3	418	4	228	5	143	6	95
2.05	898	3.05	402	4.05	223	5.05	140	6.05	94
2.10	857	3.10	387	4.10	217	5.10	137	6.10	92
2.15	817	3.15	375	4.15	212	5.15	134	6.15	90
2.20	782	3.20	364	4.20	207	5.20	131	6.20	89
2.25	744	3.25	351	4.25	202	5.25	128	6.25	87
2.30	713	3.30	340	4.30	196	5.30	126	6.30	86
2.35	683	3.35	332	4.35	192	5.35	124	6.35	84
2.40	652	3.40	321	4.40	187	5.40	121	6.40	82
2.45	627	3.45	311	4.45	183	5.45	118	6.45	81
2.50	600	3.50	302	4.50	179	5.50	116	6.50	80
2.55	578	3.55	293	4.55	174	5.55	114	6.55	79
2.60	555	3.60	286	4.60	170	5.60	112	6.60	77
2.65	532	3.65	277	4.65	166	5.65	109	6.65	76
2.70	512	3.70	269	4.70	163	5.70	107	6.70	74
2.75	495	3.75	262	4.75	159	5.75	105	6.75	73
2.80	477	3.80	255	4.80	156	5.80	103	6.80	71.5
2.85	460	3.85	248	4.85	153	5.85	101	6.85	70
2.90	444	3.90	241	4.90	149	5.90	99	6.90	69
2.95	430	3.95	235	4.95	146	5.95	97	6.95	68

**Shore Scleroscope.**—The principle of the Shore scleroscope hardness test is based upon the height of rebound of a diamond-faced hammer when dropped from a standard height upon the surface of the material to be tested. One of the great disadvantages of the scleroscope, in the author's experience, is that it requires a highly polished surface in order to obtain anywhere near accurate and comparative results. The scleroscope readings are probably more indicative of the elastic limit than of the tensile strength. The following experiments made with the scleroscope, illustrating the results to be obtained with different methods of polishing, may afford some explanation of the variations often characteristic of this instrument:

Specimen rough filed.....	readings, 25 to 30
smooth filed.....	readings, 27 to 32
rubbed with emery cloth No. 1	readings, 32
rubbed with emery paper No. 00	readings, 32
polished with diamantine.....	readings, 33

**Ballistic Test.**—The ballistic test is distinct from the static hardness tests above described in that it is a measure of the dynamic hardness by resistance to penetration under violent impact. From the author's experience with protective-deck and bullet-proof steel, the Brinell hardness is only a measure of the tensile strength and does not give a comprehensive idea of the ballistic qualities of the plate or sheet. Similarly, tests made by the Italian Government show that none of the tests mentioned in this chapter, either static or dynamic, nor their ensemble, gives a sufficient indication of the resistance which such plates will oppose in firing tests.

**Wear.**—Wear, or the hardness of material as indicated by its resistance to abrasive action, has demanded considerable attention of late on account of the increased development of high-power machines and engines. The increased weight put upon locomotive axles and rails, the higher speeding of rotating parts, and a similar tendency to wear in other machine parts have all necessitated further study of this important property of steel.

For resistance to abrasion, Robin<sup>1</sup> has arrived at the following values, these being obtained upon annealed steel with carbon contents as given, manganese—0.25 per cent. to 0.30 per cent.; phosphorus—0.015 per cent. to 0.40 per cent.; silicon—about 0.20 per cent.:

WEAR BY ABRASION. ANNEALED STEEL

Carbon Content Per Cent.	Abrasive Figure.	Carbon Content Per Cent.	Abrasive Figure.
0.07	295	0.65	308
0.12	293	0.69	280
0.25	312	0.83	258
0.38	350	1.00	252
0.60	312	1.03	252

<sup>1</sup> J. Robin, Inst. Journ., II, 1910.

This would tend to show that the wear is not proportional to the carbon content in annealed carbon steels, and that the maximum wear might be expected with steels of approximately 0.40 per cent. carbon. He further concludes from other experiments that the abrasive wear increases with the percentage of phosphorus and diminishes with the amount of manganese and silicon.



## CHAPTER II

### THE STRUCTURE OF STEEL

**Steel.**—Steel is an alloy, the principal and essential chemical constituents of which are iron and carbon. With these there are usually certain impurities, such as phosphorus, sulphur, and silicon, which have not been entirely eliminated during the process of manufacture, as well as manganese—and perhaps other alloys such as nickel and chrome—which may have been intentionally added for a definite purpose. Of the elements which go to make up ordinary steel, the manganese, phosphorus, sulphur and silicon—the impurities—generally total to about 1 per cent.; the carbon will vary from a few hundredths of 1 per cent. to about 2 per cent.; and the balance will be iron.

Furthermore, steel is not a simple substance like copper or gold, but is more like granite, in that it is made up of a number of individual grains (let us say) or “minerals,” corresponding to the quartz, mica and feldspar of the granite. Thus, in steel which has cooled slowly from a high temperature, we have “ferrite,” “cementite” and “pearlite.” And just as the relative amounts of the quartz, mica and feldspar may vary in the rocks of the granite class, so will the relative proportions of ferrite, cementite and pearlite vary in different steels according to the specific chemical composition of the steel as a whole.

**Cementite.**—As we have stated above, the carbon and iron are the essential, as well as controlling, elements in the steel—and this is particularly true of the carbon. In steels which have cooled slowly from a high temperature, the carbon is first and always combined with a definite amount of iron to form a “carbide of iron,” corresponding to the chemical symbol  $\text{Fe}_3\text{C}$ . This compound consists of 6.6 per cent. carbon and 93.4 per cent. iron, and is micrographically known as “cementite.” The balance of the iron is practically carbon-free and is known as “ferrite.”

**Pearlite.**—Now during the process of cooling at a moderate rate from a red heat, this cementite will form a *mechanical mixture* with a

definite amount of ferrite, so that the resultant will contain approximately 0.9 per cent. carbon. This new constituent is called "Pearlite" and usually consists of interstratified layers or bands of ferrite and cementite. Pearlite is regarded as a separate and distinct constituent of steel, as it forms distinct "grains" when present in any appreciable quantity, always contains this definite percentage of carbon, and—as will be explained later—is always born at a definite range of temperatures.

**Eutectoid Steels.**—From this it will be seen that a steel containing 0.9 per cent. carbon will consist entirely of pearlite. Such steels are known as "eutectoid" steels, and that ratio of carbon as the eutectoid ratio.

**Hypo-eutectoid Steels.**—Steels containing less than this eutectoid ratio of carbon will consist of a definite amount of pearlite, varying according to the carbon content of the steel proper, and the balance in "free" or "excess" ferrite. These steels are called "hypo-eutectoid" steels, as they contain less than 0.9 per cent. carbon.

**Hyper-eutectoid Steels.**—Similarly, if the carbon content exceeds 0.9 per cent. carbon, there will not be sufficient ferrite to inter-stratify with all of the cementite, so that these steels will consist of pearlite plus free cementite. Such steels are called "hyper-eutectoid" steels.

Expressing this in a different way, we may say that very low carbon steels are made up of ferrite with a little pearlite. With increase in the carbon content of the steel, the amount of pearlite will likewise increase, with a corresponding diminution in the amount of free ferrite, until at 0.9 per cent. carbon the steel will be wholly pearlitic. Beyond this point the amount of pearlite will decrease, with a corresponding increase in the amount of free cementite.

**Structure of Slowly Cooled Steels.**—In slowly cooled steels we may therefore tell with great accuracy the approximate structural composition of the steel. And, *vice versa*, knowing the relative proportions of pearlite and ferrite or cementite, as determined microscopically, we may determine the approximate carbon content of the steel.

This is represented graphically in Sauveur's diagram as shown in Fig. 1, in which the percentage carbon is represented by the abscissæ and the percentage constituents by the ordinates.

These facts are also illustrated by the photomicrographs in Figs. 2 to 9, representing the structure of slowly cooled steel of 0.06, 0.18, 0.32, 0.49, 0.57, 0.71, 0.83 and 1.46 per cent. carbon respectively. In



Figs. 3 to 7 it will be seen that the pearlite (dark; structure not brought out by the etching) gradually increases in amount, while the ferrite (light) proportionally diminishes. Fig. 8 shows a steel of the eutectoid composition in which the ferrite (dark) and the cementite (light) are interstratified with each other, there being practically no "free" ferrite such as characterized the lower carbon steels. Fig. 9 shows the structure of a 1.46 per cent. carbon steel in which the free cementite (white) occurs as a network between the grains of pearlite (dark). In Fig. 10, showing a steel of just above the eutectoid

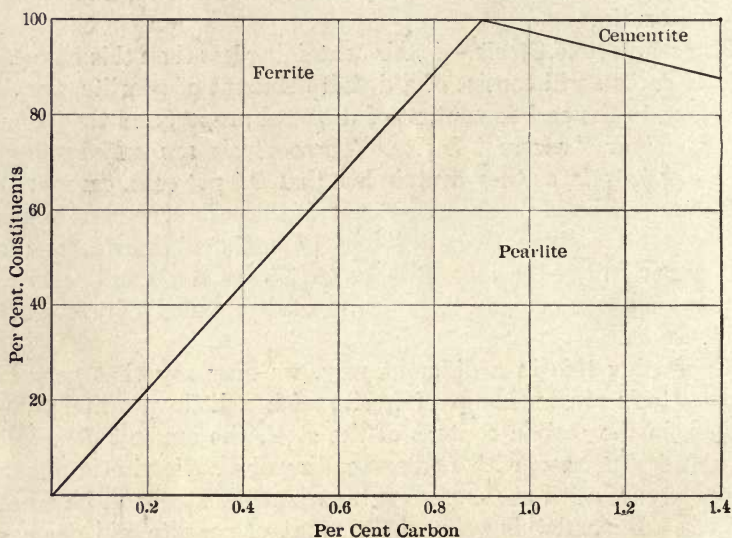


FIG. 1.—Ferrite-pearlite-cementite Diagram. (Sauveur.)

ratio, we see the first appearance of the free cementite between the pearlite crystals. In Fig. 11 we have this whole range represented by means of case carburizing a "dead soft" steel.

**Physical Properties Dependent upon Constituents.**—Upon the relative proportions of these constituents will depend the physical properties of the slowly cooled steel, neglecting for the time being their relative arrangement. Each of these components—ferrite, pearlite and cementite—has certain physical characteristics with which we must be familiar in order to gain some idea of the properties of such steels.





FIG. 2.—0.06 per cent. Carbon. Approximately Pure Ferrite.  $\times 75$ . (Ordnance Dept.)

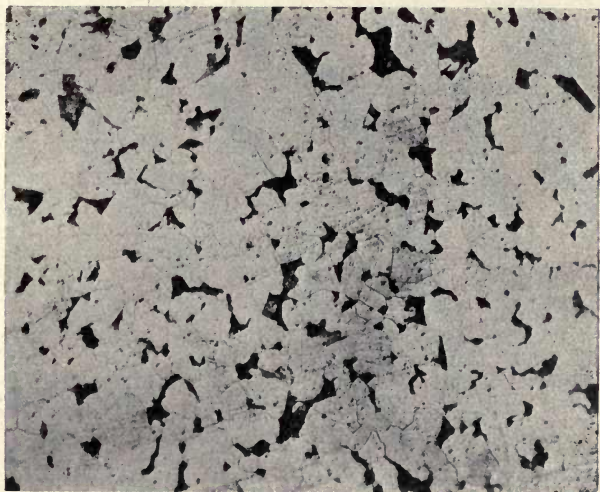


FIG. 3.—0.18 per cent. Carbon. Ferrite (White) and Pearlite (Dark).  $\times 75$ . (Ordnance Dept.)



FIG. 4.—0.32 per cent. Carbon. Ferrite (White) and Pearlite (Dark).  $\times 75$ .  
(Ordnance Dept.)

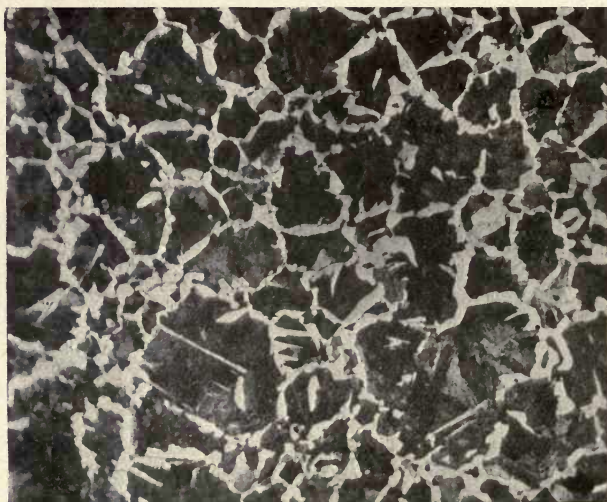


FIG. 5.—0.49 per cent. Carbon. Ferrite (White) and Pearlite (Dark).  $\times 75$ .  
(Ordnance Dept.)



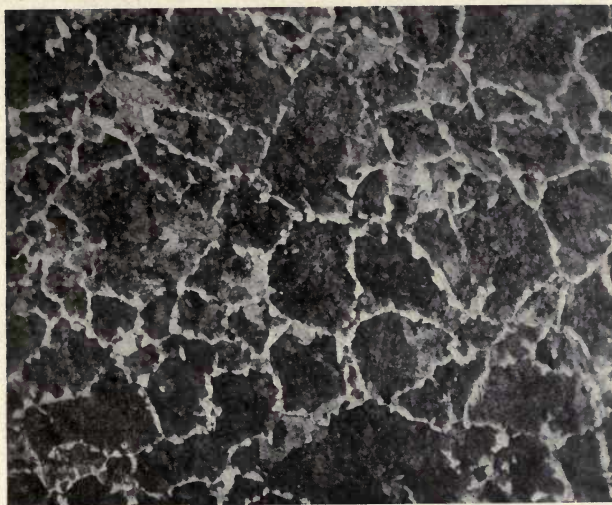


FIG. 6.—0.57 per cent. Carbon. Ferrite and Pearlite.  $\times 75$ . (Ordnance Dept.)



FIG. 7.—0.71 per cent. Carbon. Ferrite and Pearlite.  $\times 75$ . (Ordnance Dept.)



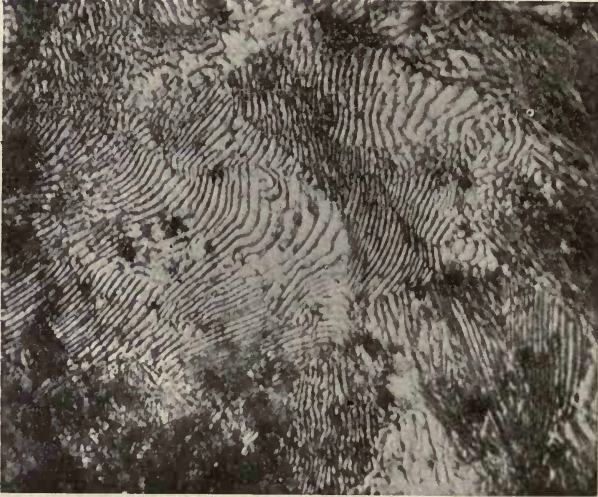


FIG. 8.—0.83 per cent. Carbon. Pearlite.  $\times 485$ . (Ordnance Dept.)

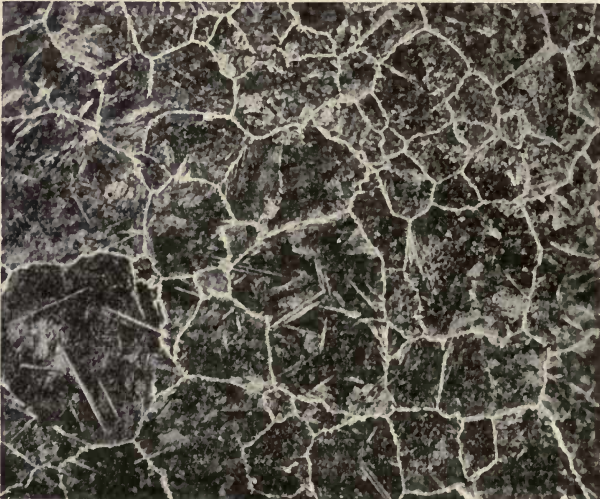


FIG. 9.—1.46 per cent. Carbon. Pearlite and Cementite (White).  $\times 75$ . (Ordnance Dept.)

**Ferrite.**—Ferrite is soft, ductile and relatively weak. It has a tensile strength of approximately 40,000 to 50,000 lbs. per square inch, with an elongation of about 40 per cent. in 2 ins. Ferrite in itself has no hardening power as applicable to industrial purposes. It is magnetic and has a high electric conductivity. Its appearance under the microscope has been shown in the photomicrographs previously mentioned—that is, as polyhedral crystals in the low carbon steels.

**Pearlite.**—As previously mentioned, the common occurrence of pearlite in slowly cooled steels is in the lamellar formation, is being



FIG. 10.—Laminated Pearlite and First Appearance (as Veins between Grains) of the Excess Cementite.  $\times 100$ . (Titanium Alloys Mfg. Co.)

composed of alternate plates of ferrite (showing dark under the microscope) and cementite (showing white under the microscope). As will be shown later, under different rates of cooling pearlite may exist in other formations and dependent upon the relative arrangement of the ferrite and cementite of which it is composed; some of these various modifications are shown in Figs. 8 and 10. Normal pearlite, that is, interstratified bands of ferrite and cementite such as shown in Fig. 8, has a tensile strength of approximately 125,000 to 130,000 lbs. per square inch, with an elongation of about 10 per cent. in 2 ins.



**Cementite.**—The properties of cementite are very little known with the exception of its great hardness and brittleness, which are a maximum. Free cementite, that is, unassociated with ferrite to form pearlite, probably does not have a tensile strength much greater than 5,000 lbs. per square inch. Its ordinary occurrence in slowly cooled steels (carbon greater than 0.9 per cent.) is either as a network, such as we have seen, or as spines and needles.

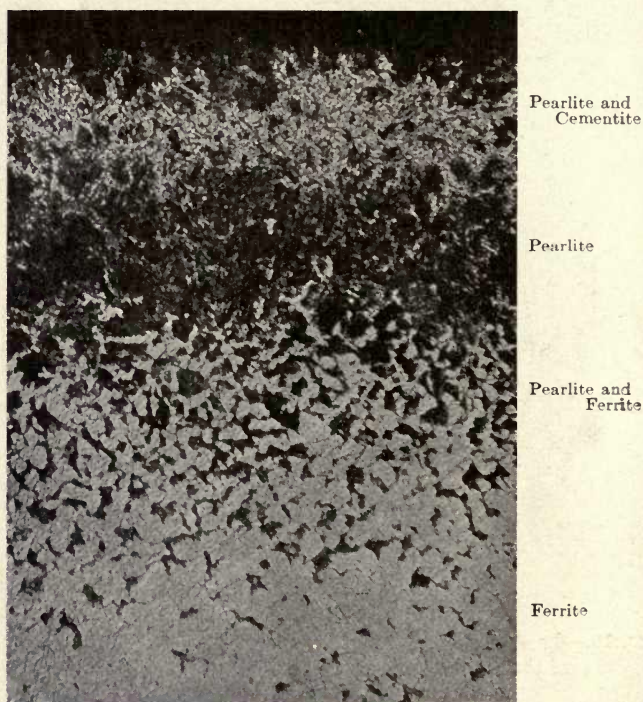


FIG. 11.—Case-carburized Steel, Showing nearly Carbonless Steel (Bottom) Gradating into High-carbon Steel (Top). (Weyl.)

**Static Strength.**—We may now sum up these facts in their relation to the static strength of slowly cooled steel as follows: Free ferrite has a minimum tensile strength with maximum ductility; pearlite has a maximum tensile strength with low ductility; free cementite confers added hardness and brittleness, with a consequent lowering of the tensile strength. In other words, by increasing the amount of pearlite in the steel, we increase the static strength but with a



corresponding decrease in the ductility. And as an increase in the amount of pearlite necessarily means an increase in the amount of carbon, the effect of increased carbon will give the same results. This is shown graphically in the diagram of Fig. 12.

**Heat Treatment.**—Heat treatment in general consists in changing or regulating the structure of the steel by various methods of

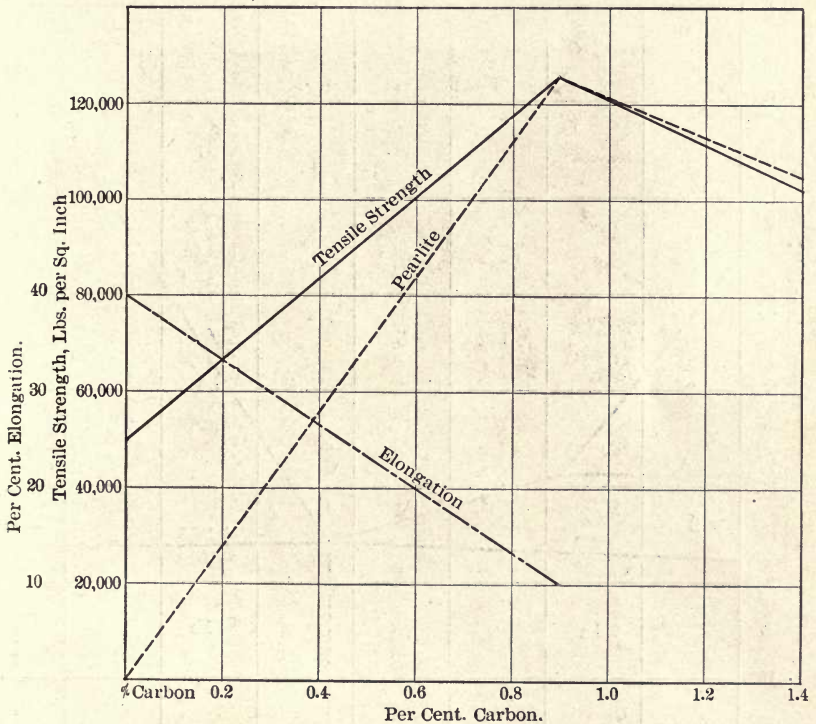


FIG. 12.—Approximate Influence of Carbon upon the Strength and Ductility of Steel.

heating and cooling. By the term “structure” is meant (1) the metallographic constituents, among which are those just described; (2) the size of the grain; (3) the net-work. In order to understand the nature of these changes and their application it will be necessary to have a clear understanding of the mechanism by which these changes are brought about.

**Critical Points.**—The nature of steel, as explained before, is complex. The structure of any particular steel may be modified

or entirely changed by various degrees of heating, and all of which take place in the steel while it is in the solid condition. These structural changes take place at temperatures known as the "critical points" or "critical ranges" of the steel. These critical ranges are denoted by the letter "A," followed by the letter "c" (abbreviation for the French word "chauffage," signifying "heating") or the

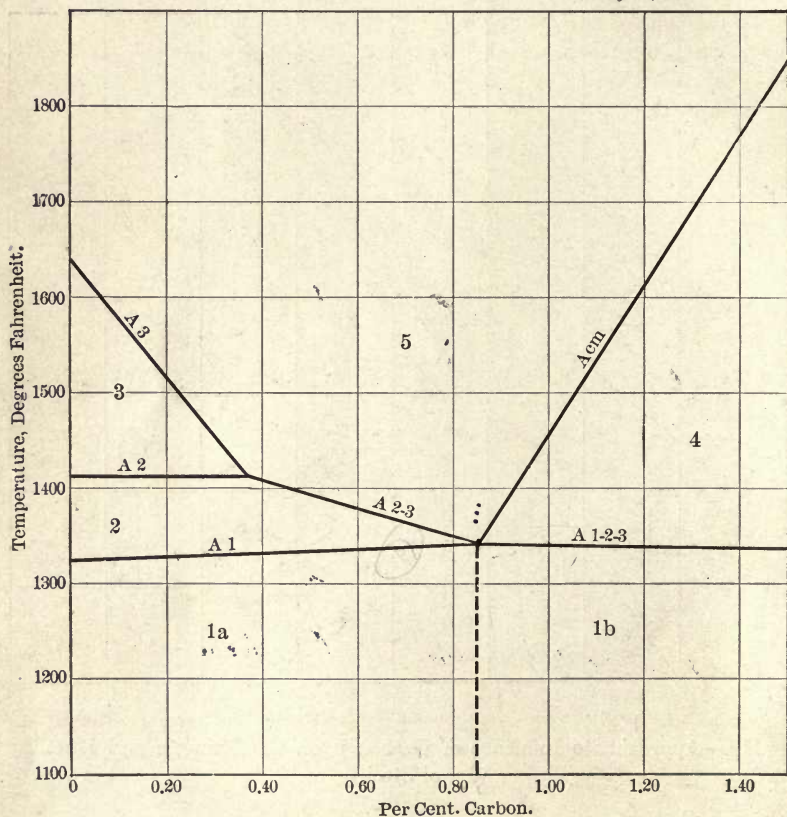


FIG. 13.—Critical Range or Carbon-Iron Diagram.

letter "r" ("refroidissement" or "cooling"). These signs, Ac or Ar, are further modified by the numerals 1, 2 or 3, indicating the particular point referred to. Thus Ac1 would mean the first critical range passed upon heating the steel beyond a certain temperature, and so forth. These critical points or ranges are indicated graphically in Fig. 13.

In considering this diagram let us devote our attention to a certain specific case, such as a low-carbon steel with about 0.2 per cent. carbon. We will also assume that the steel is in the normal condition resulting from slow cooling, in that it consists of about 25 per cent. pearlite and about 75 per cent. free ferrite. We will also first consider what is the influence which these changes occurring during the critical ranges have upon the *constituents* of the steel.

In the first place, practically no change in the constituents occurs during heating until a temperature corresponding to the lower critical range,  $A_{c1}$ , is reached, which is equivalent to about  $1330^{\circ}\text{F}$ .

In passing through this critical range there is a complete change in the nature and structure of the *pearlite*, it being converted into an entirely new constituent with new characteristics. This is technically known under the generic term of a "solid solution," micrographically called "Austenite." The *excess* ferrite remains unchanged.

**Solid Solutions.**—To understand better the nature of this new component let us consider the interaction between salt and ice. When these two substances are placed in contact with each other, we know that under suitable conditions of temperature the salt and ice merge into one another and so pass from the state of two separate substances or mechanical mixture into that of one separate substance or brine solution. A similar process takes place in the case of the pearlite, except that the resultant solution is *solid* instead of being a liquid. The individual plates of ferrite and cementite which have characterized the pearlite grains now merge into one another, forming this new substance or constituent, known as a solid solution. This new constituent, save that it is a solid and not a liquid, has all the properties of a liquid solution. Its original components are merged into a single entity, giving a complete indefiniteness of composition, and with entirely new characteristics.

**Absorptive Power of Austenite.**—Just as the brine solution can dissolve more salt or ice with increased temperature, so this solid solution of iron and iron carbide possesses the power of absorbing more free ferrite or free cementite. Therefore, as the temperature is raised above that of the lower critical range ( $A_{c1}$ ), and there being an excess of ferrite in this particular steel (0.2 per cent. carbon), the solid solution or austenite begins to absorb this ferrite. This continues progressively with increased temperature until the upper critical range,  $A_{c3}$ , is reached, or, for this particular steel, a temperature of about  $1525^{\circ}\text{F}$ . At this temperature the last of the remaining



excess of ferrite is absorbed by the austenite, so that above the upper critical range of the steel the steel is composed entirely of austenite—the solid solution.

These changes are illustrated graphically in Fig. 14. It will be seen that the initial pearlite, comprising about 25 per cent. of the normal steel, changes into austenite (the solid solution) at a temperature corresponding to that of the lower critical range,  $Ac_1$ , and then progressively absorbs the free ferrite until at a temperature corresponding to that of the upper critical range,  $Ac_3$ , the whole steel consists of austenite.

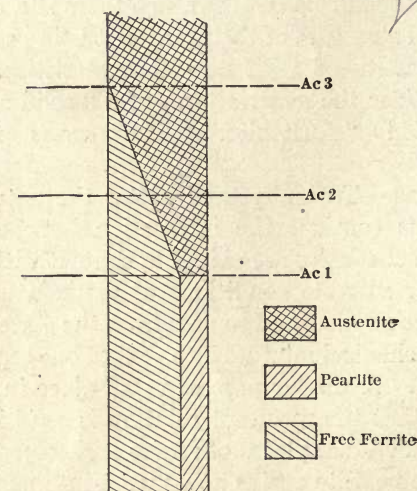


FIG. 14.—Change of Pearlite and Free Ferrite into Austenite during Heating.  
Carbon about 0.2 per cent.

These same changes are shown microscopically in Figs. 15, 16, 17 and 18. The first photomicrograph shows the normal condition of the steel, being made up of a small proportion of pearlite (dark), and a large amount of free ferrite (light). The three other structures were obtained by heating this same steel to temperatures above the lower critical range and then “fixing” the structure obtained at those temperatures by “quenching.” Fig. 16 shows the structure representative of a temperature between that of the  $Ac_1$  and  $Ac_2$ , the solid solution<sup>1</sup> (dark) having increased considerably in amount

<sup>1</sup> Strictly speaking, the dark areas thus referred to as the “solid solution” are not austenite, but its transitional stage, martensite. In the ordinary carbon steels austenite as such cannot be retained by the ordinary methods of quenching

over that of the original pearlite as in the previous figure. Fig. 17 represents the structure obtained at a temperature somewhat under that of the upper critical range,  $Ac_3$ ; in this case it will be noted that the solid solution covers nearly the whole field, there being but a small amount of the free ferrite (white). The structure representative of heating to slightly above the upper critical range is shown in Fig. 18; it will be seen that the free ferrite has now been entirely absorbed by the solid solution. Also note the extremely refined

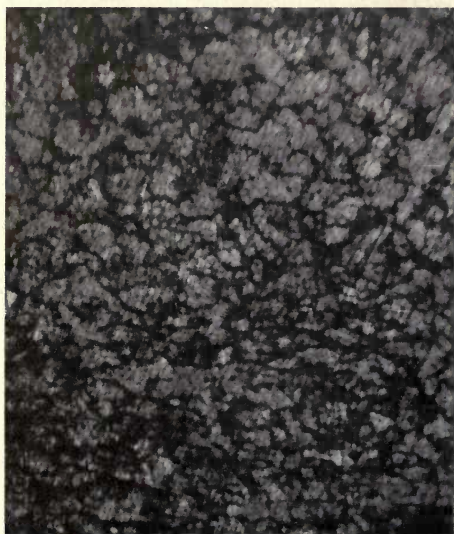


FIG. 15.—Normal Low-carbon Steel as Rolled.  $\times 60$ . (Bullens.)

structure, as we shall have occasion to refer to this particular feature a little later.

**Allotropic Modifications of Ferrite.**—Associated with these critical ranges there is also a change in the allotropic<sup>1</sup> form of the ferrite (iron). Thus pure ferrite (as distinguished from the ferrite

(as will be explained under the chapter on Hardening), but changes into martensite. Martensite, however, is also a solid solution, and for the purposes of explanation in this chapter—in order not to complicate matters—we will consider it permissible to use the term as indicated.

<sup>1</sup>Sauveur defines allotropy as “suggesting marked and sudden changes in some of the properties of a substance occurring at certain critical temperatures, without any change of state or of chemical composition.”

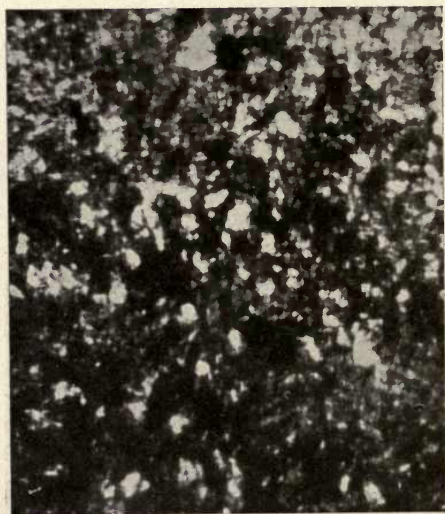


FIG. 16.—Low-carbon Steel Quenched between  $A_{c1}$  and  $A_{c2}$ .  $\times 60$ . (Bullens.).

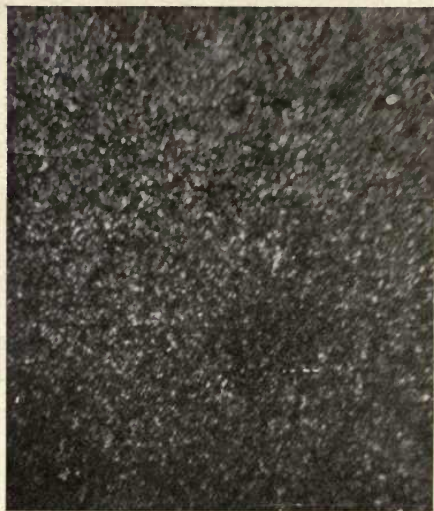


FIG. 17.—Low-carbon Steel Quenched a Little below  $A_{c3}$ .  $\times 60$ . (Bullens.)



associated with cementite to form pearlite) in its normal condition is called "alpha"-ferrite or "alpha"-iron, and is characterized by extreme ductility and magnetic properties. Upon heating this alpha-ferrite to a little over 1400° F., corresponding to the critical range Ac2, the iron becomes practically non-magnetic and is then known as "beta"-ferrite or "beta"-iron. Upon further heating to a temperature above the upper critical range, Ac3, there is still another change in the allotropic modification of the iron, it being known as "gamma"-ferrite; this gamma-iron is slightly softer than the beta modification. Gamma-iron has the property of being able

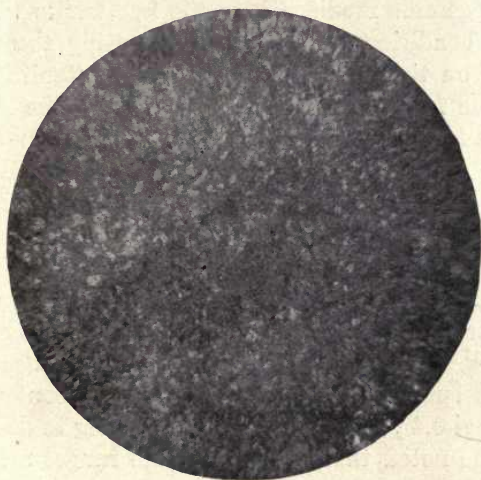


FIG. 18.—Low-carbon Steel Quenched above A3.  $\times 60$ . (Bullens.)

to dissolve carbon or iron carbide, a characteristic which is not held by alpha-iron.

**Merging of the Critical Points.**—Now by referring to the carbon-iron diagram in Fig. 13 it will be noted that at the eutectoid ratio of carbon, that is, at about 0.9 per cent. carbon,<sup>1</sup> the three critical ranges A1, A2, and A3, merge into one. That is, steels consisting of pearlite alone, when heated to a temperature beyond this point, will change directly into the solid solution austenite, which will consist of a solution of carbide (or carbon, according to some authorities) in

<sup>1</sup> The eutectoid ratio on the chart is given as 0.85 per cent. carbon. According to the authority selected this ratio will vary between 0.8 and 0.9 per cent. carbon; but the more recent tendency is to adopt 0.90 per cent.

gamma-iron. Similarly, as normal pearlite always represents this eutectoid ratio, the same change of pearlite into a solid solution of carbide in gamma-iron will always occur at this temperature in ordinary carbon steels irrespective of the carbon content of the steel as a whole.

**Changes in Heating Different Steels.**—With this explanation clearly in mind, we may now refer back to the example of the 0.2 per cent. carbon steel and more fully explain the changes which take place in the constituents. Under normal conditions, this steel will consist of pearlite plus alpha-ferrite. Upon heating through the  $A_{c1}$  range, the pearlite will change into austenite, the iron of which will be in the gamma modification; the free ferrite will still remain in the alpha condition. Upon further heating through the zone marked "2" on the diagram Fig. 13, the austenite will begin to absorb the free ferrite. Upon passing through the  $A_{c2}$  range the balance of the free ferrite will pass from the alpha modification into that of beta-ferrite; the steel as a whole will be hard and non-magnetic. Upon further heating (zone 3) the remnant of the beta free ferrite will be gradually absorbed, so that on passing through the critical range,  $A_{c3}$ , the whole steel will be in the condition of austenite (zone 5), or a solution of iron carbide (or carbon) in gamma-iron.

In a similar manner we might explain the changes in constituents which take place upon heating normal steel with any carbon up to that of the eutectoid ratio. With a carbon content somewhere between 0.3 and 0.4 per cent. (varying according to different authorities) it will be noted that the  $A_2$  and  $A_3$  ranges merge into one, known as  $A_{2-3}$ .

In a manner analogous to the absorption of free ferrite by the solid solution in the hypo-eutectoid steels, the free cementite will be absorbed in the case of the hyper-eutectoid steels, the final solution taking place at a temperature range indicated by the line  $A_{cm}$ . The only difference, and that a practical one, is that the solution of the free cementite takes place more sluggishly than the solution of the free ferrite of the lower carbon steels.

**The Ar Ranges.**—Corresponding critical changes take place upon cooling slowly from above the upper critical range, except that they occur in the reverse order and with opposite effect. On account of the molecular inertia, however, we find that these critical ranges (of cooling,  $Ar_3$ ,  $Ar_2$ ,  $Ar_1$ , etc.) are a number of degrees below the temperatures at which they appeared on heating. This difference is dependent upon length of exposure and the temperature to which



the steel was subjected, the rate of cooling, and, more particularly, upon the influence of the alloying elements which may have been added to the steel. Some of the alloys, if present in sufficient amount, will cause the recalescent points to fall below normal temperatures, and are the basis of air-hardening steels and similar compositions.

**Changes on Slow Cooling.**—Upon slow cooling from above the upper critical range, the solid solution will commence to reject the excess ferrite (or, of course, the excess cementite in the case of hyper-eutectoid steels) as the temperature decreases from  $Ar_3$  to  $Ar_1$ . The reverse changes in the physical nature and properties of the iron occur at the critical ranges during cooling as those previously noted under heating. When the lower critical range is reached, the excess ferrite or cementite will have been entirely rejected, and as the steel passes downward through this range (or point), the solid solution—now containing 0.9 per cent. carbon—will change into pearlite. Under similar conditions of cooling, the original steel and the present heated and cooled steel will have the same structure.

**Refinement.**—Before leaving the subject of the influence which heating through these various critical ranges has upon the structure of the steel, there are a few points which we wish to mention briefly concerning refinement. Again assuming that the steel is in the normal condition, no change will take place in the structure until the temperature has been raised at least to that of the lower critical range. At this temperature the original pearlite grains are completely changed and will possess that maximum refinement which the formation of the austenite can impart—that is, *complete* refinement. If the steel has a carbon content other than that of the eutectoid ratio (i.e., contains free ferrite or free cementite), the *steel as a whole will not be refined*; the excess ferrite or cementite will remain unaltered and the steel will retain its original grain-size. This is brought out by a comparison of Figs. 15 and 16. Complete refinement of the steel as a whole will not result until the steel has been heated to a temperature slightly over that of the upper critical range, as a comparison of Figs. 17 and 18 will prove, and as is evident from previous discussion. A clear understanding of these principles must be had, as they form the basis of many of the heat treatment processes which will be later developed.

**Grain-Size Beyond  $Ac_3$ .**—As the temperature is progressively raised above the critical range, a gradual coarsening of the austenite grains occurs. This increase size is not only a function of the temperature, but also of the length of time at which the high tem-



perature is maintained. The practical application of the principles noted in this and the previous sections will be considered in the chapter on Annealing.

**Network.**—The third factor in the structural changes taking place upon heating is the effect of temperature upon the network. All hypo-eutectoid steels in the normal condition are made up of pearlite with a varying amount of excess ferrite, the latter decreasing with the increase in carbon content. From our study of the inter-

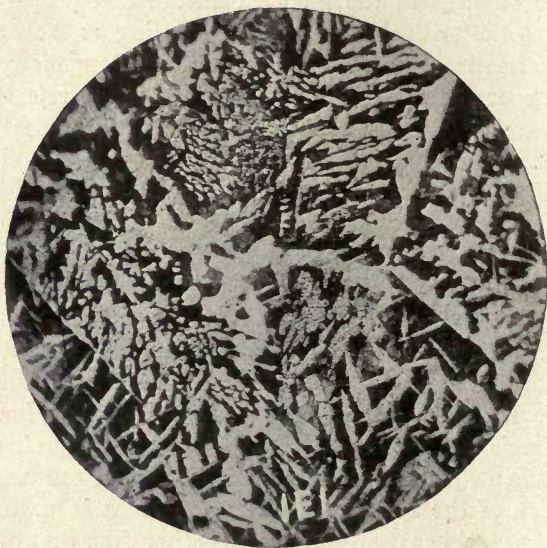


FIG. 19.—Microstructure of Cast-steel Ingot as Cast.  $\times 75$ . (Ordnance Dept.)  
Tensile Strength, 77,000. Elastic Limit, 39,000. Elongation, 10.5.  
Red. of Area, 16.9.

nal mechanism by which the constituents of the steel are formed by slow cooling, we know that the pearlite forms the basis of the structure, the ferrite being rejected by the solid solution (pre-pearlite). Being thrown out to the boundaries of these austenitic grains, the excess ferrite forms a network around these grains. Upon reheating, this network is gradually absorbed, its final absorption taking place upon passing the upper critical range. This change is similar to that explained previously under the description of the action of the excess ferrite.

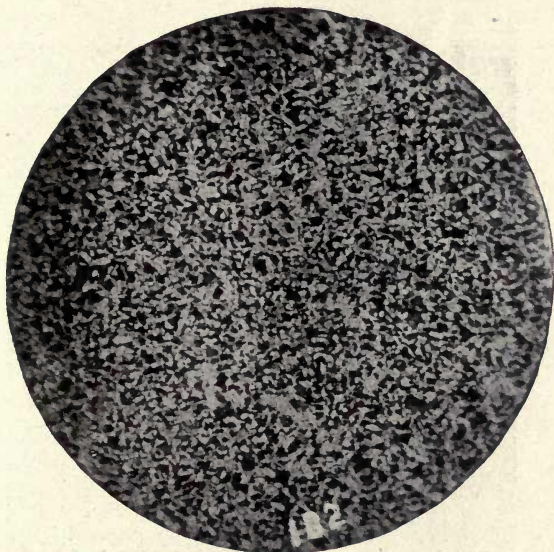


FIG. 20.—Microstructure of Cast Steel Ingot Forged to 1450° F.  $\times 75$ . (Ordnance Dept.) Tensile Strength, 83,500. Elastic Limit, 50,500. Elongation, 27.5. Red. of Area, 43.3.

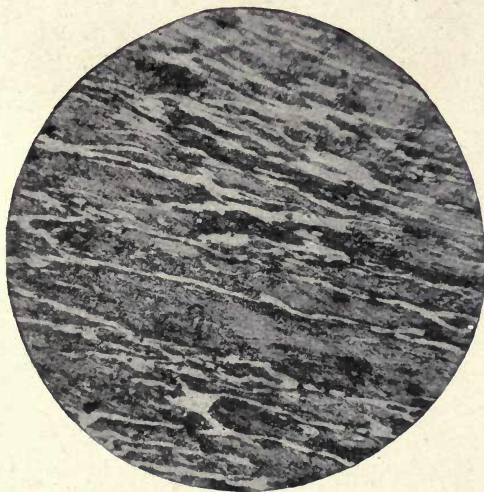


FIG. 21.—Microstructure of Steel Subjected to Cold Work, and Showing Distortion of Grain.  $\times 50$ . (Ordnance Dept.)





FIG. 22.—Hammer-hardened Steel, 0.46 per cent. Carbon.  $\times 300$ . (Savoia.)

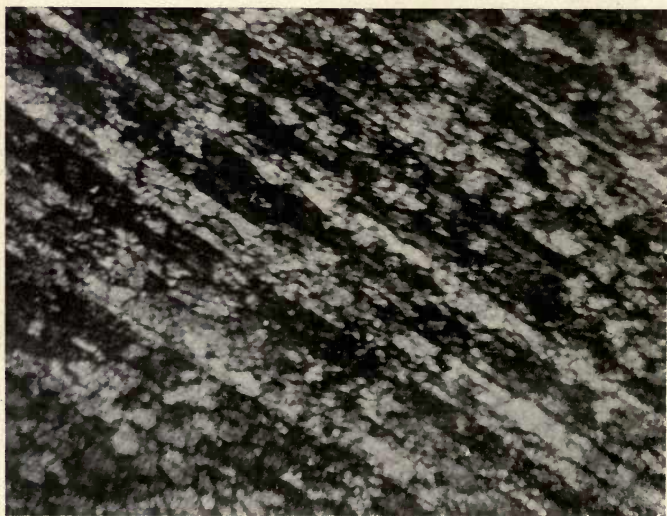


FIG. 23.—Effect of Cold Rolling on 0.20 per cent. Carbon Steel.  $\times 60$ .  
(Bullens.)





FIG. 24.—Effect of Punching upon Structure of  $\frac{5}{32}$ -in. Chrome-nickel Steel Plate. Hole Downwards and at Right.  $\times 50$ . (Bullens.)

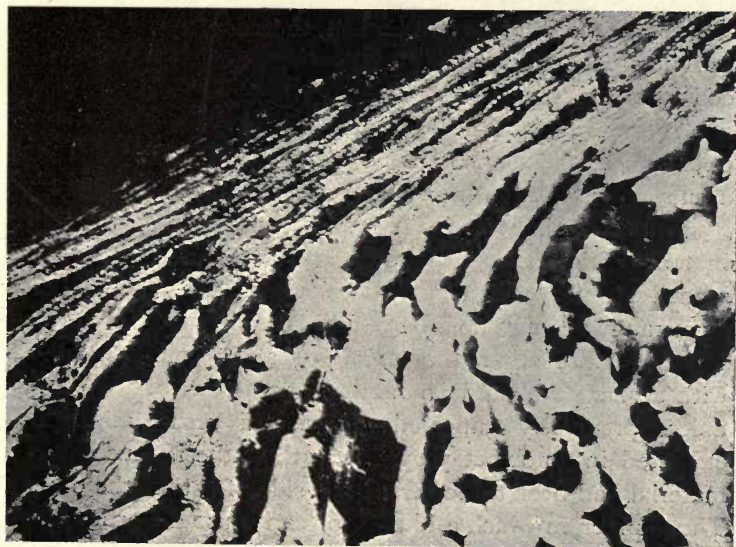


FIG. 25.—Machining Strains on Surface of Mild Steel. (Brearley.)

**The Effect of Work on Grain-Size.**<sup>1</sup>—Steel cooled slowly and undisturbed from a high temperature will show a coarsely granular or crystalline structure, and the size of the grain is a function of the temperature and time during which the material is held at the maximum temperature, and the rate at which the material is cooled. In large masses of material the structure will be coarser in the center than at the surface, due to the difference in rate of cooling. In order to overcome this difference and at the same time produce a homogeneous, uniform material, the steel is worked during the period at which grain growth would ordinarily take place. Steel which has been hot-worked down to the Ar1 point will show a finer grain, and will be stronger than the same steel slowly cooled without work, and will at the same time show high ductility. Examples of steel worked and unworked are shown in the photomicrographs of Figs. 19 and 20.

Steel which has been worked below the Ar1 range—that is, cold-worked—will show considerable distortion of grain, as is illustrated by Fig. 21, and may even become hardened, Fig. 22. Cold rolling frequently develops a weak, laminated structure, as is shown in Fig. 23. Even punching or machining operations may greatly affect the structure, examples of which are given in Figs. 24 and 25.

<sup>1</sup>In part from Bulletin 1961, Ordnance Dept.

## CHAPTER III

### ANNEALING

**Annealing.**—Annealing, in its commercial application, may have for its purpose any or all of the following aims: (1) to “soften” the steel and thus put it in condition for machining or to meet certain physical specifications; (2) to relieve any internal stresses or strains caused by previous hardening or elaborating operations; (3) to obtain the maximum refinement of the grain in combination with large ductility.

Thus, depending upon the results desired, *commercial annealing* will consist of a heating operation carried to some predetermined temperature—although not necessarily over the critical range—to produce the results desired in items 1 and 2 previously noted, and followed by a moderately slow cooling of the metal from that temperature. *True or full annealing* requires a heating to above the upper critical range of the steel.

**Elemental Considerations.**—In the abstract, annealing would appear to be but a suitable correlation of the following elements:

1. Rate of heating;
2. Temperature of heating;
3. Length of heating;
4. Rate of cooling.

But in actual practice the success to be attained in annealing (or in any heat treatment process, for that matter) must depend upon the judgment and skill of the furnace operator in applying the basic principles which may be derived from a consideration of the above factors. Thus it is the man who determines the manner of placing the charge in the furnace, of regulating the flow and composition of the hot gases, of determining when the steel has been uniformly and thoroughly heated, and similar fundamentals. For while it is advisable and perhaps necessary to understand the theory behind the actual work itself—the “wherefore”—the “wherewithal” is largely a personal equation and should be borne in mind throughout every theoretic discussion of principles or practice.



**Heat Application.**—The manner in which the steel is placed in the furnace is a factor of supreme importance. It may even be said that three different kinds of annealing may be produced in the same furnace operating at the same indicated pyrometer reading, dependent simply upon the method of placing the stock in the furnace. Particular stress should be laid upon the necessity for getting heat to the center and bottom of the charge, not only for the sake of uniform annealing, but also to shorten the time of absorption and lessen the time of exposing the top and outside edges of the charge to the heat and influences of the chamber atmosphere. Thus it has been shown that a uniform chamber temperature does not necessarily mean a uniformly annealed product; that a circulation of heat through the mass is more desirable than the mere application from the outside; that, with the same chamber uniformity, it is possible to vary the quality of the anneal by the manner in which the stock is placed in the annealing zone. It is advisable to raise the charge above the furnace floor or hearth upon suitable blocks or supports, to separate each piece from the other, and to avoid localized heating through over-loading. It is only by such means that there will be provided an opportunity for the circulation of the hot gases through the charge.

**Pre-Heating.**—Slow, careful and uniform heating is always advisable regardless of the chemical composition or physical condition of the steel. Heating to such temperatures as are common in general annealing practice necessarily results in more or less change of physical condition or molecular readjustment, and the greater the hardness, brittleness and amount of internal strain in the metal, the greater will be the deleterious effect of such heating. Thus objects of intricate design, or with varying cross-sections, or steel in a hard, brittle condition, should be given the greatest care in heating in order that the release of any strains shall not cause warpage or otherwise injure the metal. Such pieces should never be placed directly in a hot furnace, but should be given a careful pre-heating.

#### ANNEALING HYPO-EUTECTOID STEELS

**Microscopic Changes.**—In the previous chapter we have explained that, in the ordinary cast, rolled or forged sections (pearlitic in character), there is virtually no change in grain size or in constituents during the heating to a temperature below that of the lower critical range  $A_{c1}$ . That is, there is no refinement of the steel.

As the temperature passes the Ac1 range there occurs the complete change of the pearlite to the solid solution, giving the maximum refinement to the austenite.

Passing through zone 2 (Refer to Fig. 13) the excess ferrite is progressively absorbed by the solid solution, causing an apparent decrease in the grain-size of the steel as a whole. This absorption is the slower the greater the carbon until the carbon nears 0.85 per cent., but is offset by the fact that the amount of free ferrite decreases as the eutectoid ratio is approached.

Upon passing through the critical range Ac2 we have the formation of beta iron with no apparent change between the relative grain-size of the alpha ferrite and beta ferrite grains. The same absorption of the excess ferrite continues progressively, but with increased sluggishness (due to the supposed properties of beta ferrite). This applies to steels with say 0.12 to 0.30 per cent. carbon. In the very low carbon steels Howe<sup>1</sup> sums up the probable changes during this period in a provisional proposition that (a) if initially fine-grained the steel coarsens, though only very slowly; (b) if initially coarse-grained it refines slowly; (c) to coarsen again upon long exposure to these temperatures.

The changes taking place through zone 2 continue through zone 3, although more slowly. If the rate of heating through this range of temperatures is comparatively slow, there will be a complete absorption of the remaining ferrite just before Ac3 is reached. Under ordinary circumstances final absorption will occur on passing through the Ac3 range.

**The Upper Critical Range.**—As the steel passes the upper critical range there is the complete refining of the grain, it becoming very fine and almost amorphous. As the temperature increases beyond this range the grain-size coarsens, causing a diminution in the strength of the steel. The effect upon the physical properties of the steel is great. The tensile strength is increased somewhat as the temperature advances. The elastic limit rises until a point is reached about 175° to 200° F. over the upper critical range, after which it then decreases. The elongation and reduction of area decrease very rapidly. These changes in the physical properties are shown graphically in Fig. 26 in which the results obtained by heating a 0.40 per cent. carbon, basic open-hearth steel to a definite temperature and then slow-cooling with the furnace are plotted

<sup>1</sup> H. M. Howe, "Life History of Network and Ferrite Grains in Carbon Steel," Proc. A. S. T. M., Vol. XI, 1911.



against the temperatures. It will be noted that the softest and most ductile steel is obtained at approximately 1475° F., which is about 50° over the upper critical range.

**Heating Over the Upper Critical Range.**—The effect of heating beyond the critical range is well developed by the series of photographs (by Howe) shown in Figs. 27, 28, 29, 30 and 31. The steel (0.40 per cent. carbon, 0.16 per cent. manganese) was heated to the

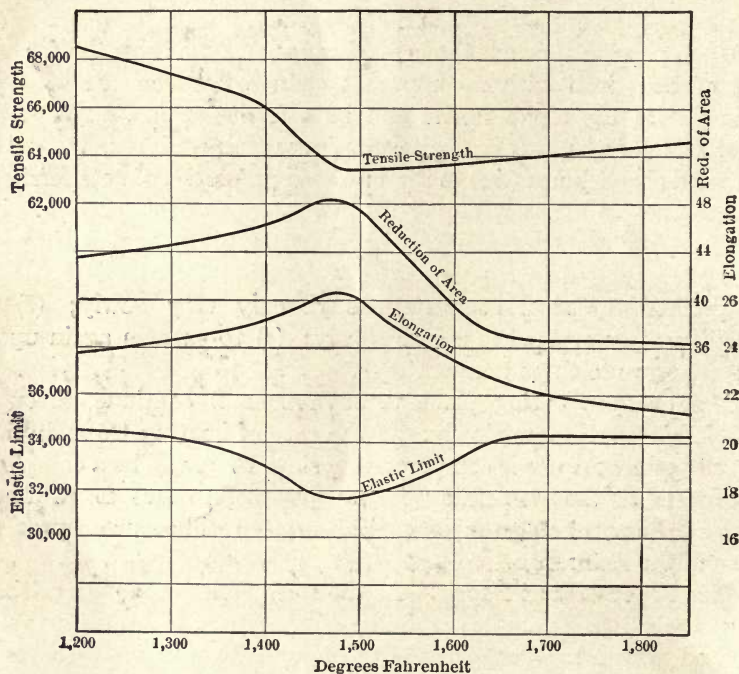


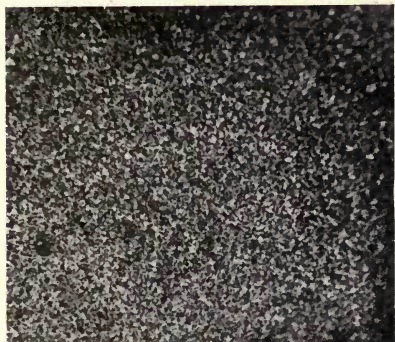
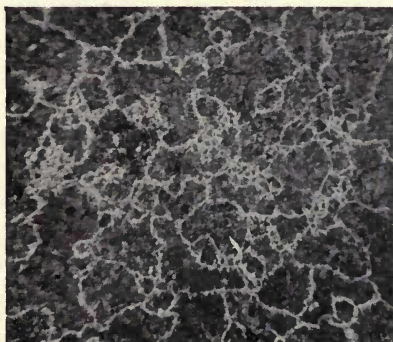
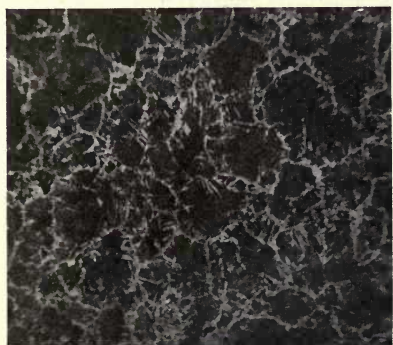
FIG. 26.—Effect of Annealing Temperature on Physical Properties.

temperatures indicated, held at those temperatures for ten minutes, and then cooled in air. There is a difference in grain-size between that cooled from 1472° F. and from 1652° F., showing that annealing should never be carried very far beyond the upper critical range or Ac<sub>3</sub> point unless for special reasons. As the high temperatures were successively raised to 1832° and 2012° the grain-size becomes noticeably larger, until at 2192° the steel is "burnt." These photomicrographs also exhibit the effect of air cooling upon the structure, in that it develops a distinct net-work or cellular structure. The effect of heating beyond the upper critical range is also brought



EFFECT OF HEATING BEYOND  $A_{c3}$ .

0.40 per cent. Carbon Steel Heated at Temperatures Indicated for Ten Minutes and Air Cooled.

FIG. 27.—1472° F.  $\times 40$ . (Howe.)FIG. 28.—1652° F.  $\times 40$ . (Howe.)FIG. 29.—1832° F.  $\times 40$ . (Howe.)FIG. 30.—2012° F.  $\times 40$ . (Howe.)FIG. 31.—2192° F.  $\times 40$ . (Howe.)

out in an analogous manner by Figs. 32, 33, 34, 35 and 36, except that in this case the steel has been cooled very slowly (furnace cooled) from the specific temperatures.

**Use of the Microscope for Checking Structural Changes.**—From previous theoretical discussion, it is evident that in order to fulfill the true or full annealing operation, it is necessary to heat the metal to over the upper critical range of the steel in order to obtain the complete change of structure with the smallest grain-size possible. The microscopic changes which take place during such heating of a 0.28 per cent. carbon steel are given as follows:

Temperature.	Structure.
1325° F.	Very coarse ferrite and pearlite similar to the original bar.
1375° F.	Laminæ of ferrite strong, ground-mass refined.
1425° F.	About 25 per cent. ferrite laminæ left.
1475° F.	Trace of coarse ferrite unabsorbed.
1500° F.	Complete refining. No coarse ferrite.
1550° F.	Structure similar.
1650° F.	Refined but grain-size coarsening.

These experiments<sup>1</sup> were carried out with a view to discover the cause of failure of an eye-bar (carbon 0.28 per cent.) when placed in service. The original steel had been annealed several times at temperatures under the upper critical range, but a microscopic study showed that these heatings had simply refined the pearlitic ground-mass. In other words, it was found that the proper annealing temperature necessary to obtain a completely refined steel was beyond the upper critical range. In this steel it would seem to be about 1500° F. The lower critical range is shown by the refining of the ground-mass which occurred between 1325° and 1375°.

**Diffusion.**—We have repeatedly stated that complete absorption of the excess ferrite takes place at the upper critical range of the steel. Although this statement is true, there is another phase of this absorption to be considered, and a full understanding of which will probably clear up many of the questions which have perplexed those unfamiliar with the theory of annealing. This phenomenon may be called "diffusion." Let us hark back to our former simile

<sup>1</sup> Wm. Campbell, "Further Notes on the Annealing of Steel," Proc. A. S. T. M., Vol. X, 1910.



EFFECT OF HEATING BEYOND  $A_{c3}$ .  
 0.40 per cent. Carbon Steel Heated at Temperatures Indicated for Ten Minutes and  
 FURNACE COOLED.

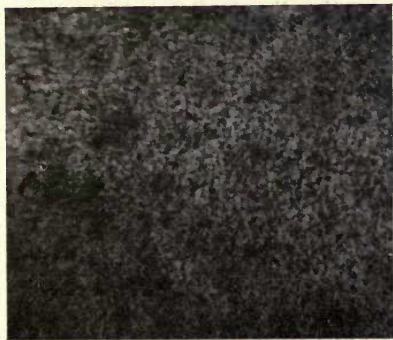


FIG. 32.—1472° F.  $\times 40$ . (Howe.)



FIG. 33.—1652° F.  $\times 40$ . (Howe.)

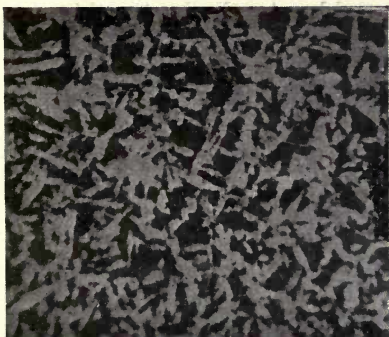


FIG. 34.—1832° F.  $\times 40$ . (Howe.)



FIG. 35.—2012° F.  $\times 40$ . (Howe.)



FIG. 36.—2192° F.  $\times 40$ . (Howe.)



of the salt and brine solution. When a grain of salt is dissolved by the brine, it is the solution in the immediate neighborhood of the salt crystal which acts as the solvent and not the entire volume of the brine solution. In time, however, the dissolved salt will eventually diffuse through the whole body of brine and the brine will then be of equal composition throughout. Now a similar process is going on in the steel when the solid solution (austenite) is absorbing the excess ferrite, and it will be found that *complete absorption may not mean complete diffusion or equalization*. The process of equalization goes on with the rise in temperature. If the passage through temperatures under that of the upper critical range is only slow enough, a large part of the diffusion will have occurred by the time  $Ac_3$  is reached. In order that there may be complete diffusion, and therefore complete grain-refining, the sojourn at a temperature approximating  $Ac_3$  must be long enough for this complete diffusion of the absorbed excess ferrite and therefore of the solid solution. Although exposure to a higher temperature would naturally hasten this diffusion, it would be at a cost of coarsening the austenite grains. The effects of non-equalization will be discussed in a later part of the chapter.

**Rate of Heating.**—Studying the rate of heating from the practical aspect there is also another factor to be considered—that of bringing the whole mass of the steel to the proper temperature evenly. It is self-evident that the center of a large mass of steel, such as locomotive axles or steel blooms, will lag in temperature behind the exterior. In other words, it is the tendency of the core to be considerably lower in temperature than the shell or outside of the steel. It is then a common procedure to raise the temperature of the furnace beyond the proper annealing heat in order to drive the heat to the center of the piece to be annealed. This is a great mistake. It is far better to take the extra time required to heat more slowly as the proper temperature is neared, thus bringing the steel to an even temperature throughout. If this were not done, the exterior of the piece might be carried beyond the proper temperature—and, in general, a needlessly high temperature is injurious and tends to recoarsen the grain.

Expressing this question in a different way, we may say that the furnace in which the metal is being heated for annealing should in no case be run at a higher indicated temperature than the maximum temperature to which the metal itself is to be heated. To illustrate: a piece of steel heats, cools and decarbonizes on the corners first.

The life of the entire piece of steel is no greater than the life of the corners. If the steel is placed in a hot furnace, the corners are apt to be heated long before the major part of the mass. If the temperature is high, the corners are overheated before the center of the mass is saturated. From this commonplace example there should be indicated the necessity for slow, soaking heats in order to prevent overheating the corners of the metal, and further, the necessity of soft hazy heats to prevent oxidation or decarburization of the exposed edges.

**Temperature of Heating.**—Assuming that the proper degree of care has been used in heating the steel, the next question is the degree of heat necessary. Reduced to lowest terms, the true or full annealing operation requires the production of an entirely new crystalline structure, the constituents of which shall be of the smallest grain-size attainable; this operation should also eliminate all internal strains and stresses. As previously described, this new structure is given birth at a temperature known as the “upper critical range” of the steel. The exact temperature<sup>1</sup> will depend upon the chemical composition of the steel, and, more particularly, upon the carbon content. As this transformation does not occur suddenly, but usually covers a range of some 25° to 50° it is customary to adopt a temperature of about 50° over the upper critical range as the proper annealing heat. For straight-carbon steels these may be roughly given as shown in the chart in Fig. 37. The upper critical range is approximately located by the dash line on the chart.

The temperatures recommended by the American Society for Testing Materials<sup>2</sup> are as follows:

Range of Carbon Content.	Range of Annealing Temperature.
Less than 0.12 per cent.	1607° to 1697° F.
0.12 to 0.29	1544° to 1598° F.
0.30 to 0.49	1499° to 1544° F.
0.50 to 1.00	1454° to 1499° F.

<sup>1</sup> Methods for determining the critical ranges are described in Chapter XVIII.

<sup>2</sup> It will be noticed that the temperatures recommended by A. S. T. M. are distinctly higher—especially for the tool-steel grades—than those advised by the author. In the light of my own experience, and that of others, I believe that the lower the temperature which can be used to give the desired results, the greater will be the maximum efficiency of the annealed steel.

**Length of Heating.**—Ordinarily the underlying practice of this part of the operation is to heat the steel until the whole mass has been heated uniformly throughout at the proper temperature. This will of course depend upon the size of the object. This full heating is generally sufficient to give birth to the new grain structure and relieve all internal stresses. The proper rate of cooling should then maintain the steel in that condition. If the steel should be quenched in some hardening bath such as oil or water, this new grain-size and rear-

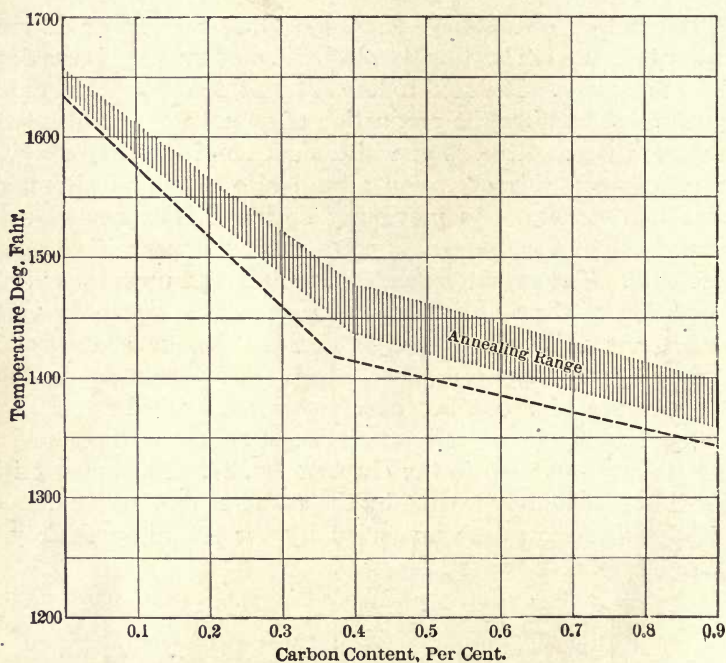


FIG. 37.—Annealing Range for Carbon Steels.

rangement of the structure would be kept. The annealing operation should theoretically bring about approximately the same results as to grain-size, neglecting for the moment the effect of slow cooling through the transformation ranges. From the standpoint of practice, however, much difficulty is experienced in this regard, particularly in cases where the mechanical work upon the steel has been severe, and also in alloy steels.

It seems that the greater the internal stress upon the steel the greater is the amount of intermolecular lag or final release of this



stress behind the actual change of constituents. That is, even though a totally new structure may be set up by the annealing temperature, there remains for a considerable length of time a tendency of the new

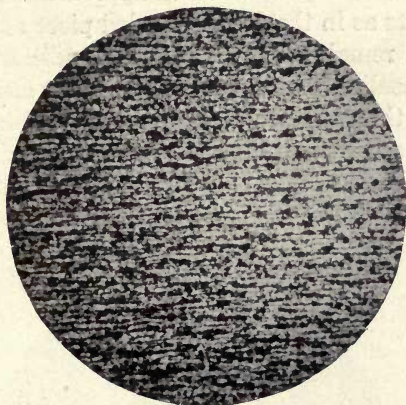


FIG. 38.—Frame Steel as Rolled.  $\times 60$ . (Bullens.)

structure to return, upon slow cooling, to the stressed condition of the original, even though the constituents themselves may be those born at the new temperature.



FIG. 39.—Frame Steel Partly Annealed.  $\times 60$ . (Bullens.)

This point is illustrated in Figs. 38, 39 and 40. These are photomicrographs taken from tests made upon chrome nickel steel plates for automobile frames: Fig. 38 shows the structure of the steel

as rolled; Fig. 39 shows the steel after a short annealing at a temperature above the upper critical range; and Fig. 40 shows the same steel after a long anneal at the same temperature. It will be noticed that the steel in Fig. 39 has taken on approximately the same structural constituents as in the fully annealed piece as shown in Fig. 40, but that it still remains in the stressed condition of Fig. 38, even though the annealing temperatures were the same in both cases. It is important, therefore, if a soft steel, free from all internal strains and stresses is desired, that a sufficient length of time be allowed for the permanent elimination of these intermolecular strains, before and after cooling. In the case of the steel plate just referred to it re-

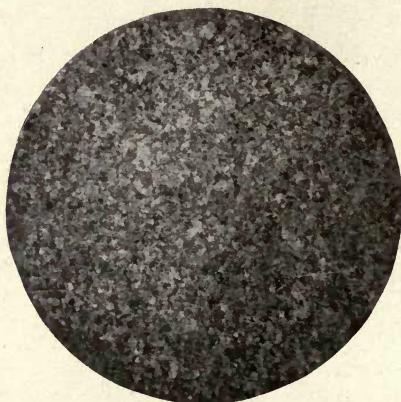


FIG. 40.—Frame Steel Fully Annealed.  $\times 60$ . (Bullens.)

quired some twelve hours for the complete change or equalization to take place!

**“Milky-Ways.”**—We have previously explained this same phenomenon under the heading of “Diffusion,” as this is the scientific principle underlying it. The reoccurrence or reformation of these laminations or other stressed structures is due to the fact that the complete effacement by equalization had not taken place. In other words, it means that where these stressed areas occur the carbon content as a whole is less than in the rest of the mass. Where ferrite predominates, as in the lower carbon steels, there will the mass more easily coalesce into what may be termed “milky-ways” (Howe). In order to equalize the steel as a whole the length of time of the sojourn at or slightly above  $Ac_3$  should be inversely proportional to the time occupied in reaching that temperature.

**Alloy Steel.**—Alloy steel is particularly an example of the retarded transformation as described above, although the author has repeatedly found it in carbon steels cold worked. Most notable of the alloy steels exhibiting this peculiarity are chrome, chrome-nickel and chrome-vanadium steels. Many users and even manufacturers of these steels contend that annealing will not give entirely satisfactory results. The oft-encountered "hard-spots" would seem to bear out this dispute. From the experience of the author the proposition develops into a simple question of time. The alloying metals add to the density of the grain, so that a longer time is needed to complete the change in entirety. It was found that a certain 3-inch rolled-round approximating 0.50 per cent. carbon, 1.50 per cent. nickel and 0.50 per cent. chrome required sixteen hours for this complete change, together with the elimination of hard-spots, to take place; high-carbon high-chrome steel often takes days for a complete anneal.

**Time of Heating.**—Assuming a proper rate of heating, it therefore remains to determine the required length of heating by means of experimentation, taking into consideration such points as have been mentioned above. Along these lines some interesting experiments have been carried out by Mr. M. E. Leeds<sup>1</sup> for the determination of the variations in rates of heating of specimens of different sizes to various furnace temperatures and which in some degree answer the oft-repeated question "How long shall we heat this piece of steel?" The experiments were made with round specimens of normal open-hearth carbon steel approximating 0.5 per cent. carbon, and ranging in size from 2 ins. to 12 ins. in diameter, by 24 ins. long. Each specimen was heated to four temperatures, namely, 1000°, 1200°, 1400°, and 1600° F. During the time of heating a continuous record was kept of furnace temperatures, the temperature of the surface of the specimen, and of one to three points in its interior. While the results obtained are necessarily of relative value only on account of the varying furnace conditions which might be found elsewhere, there are, nevertheless, several interesting conclusions of value which were drawn from these experiments:

1. **"Variation in Time of Heating with Size.**—As would be expected, the smaller specimens heat more rapidly than the larger. In curves (Fig. 41) the relation between the size of specimen and time of heating to various temperatures are brought out. Except in a very general way, this information could not be used as a guide

<sup>1</sup> M. E. Leeds, A. S. T. M., June Meeting, 1915.



to heating practice, as the rates would vary with the size of furnace and probably with other conditions.

2. "Relation between Time of Heating and Furnace Temperature.—The time of heating for a specimen of any size is less when it is brought up to 1600° F. than when brought up to 1200° F., and less

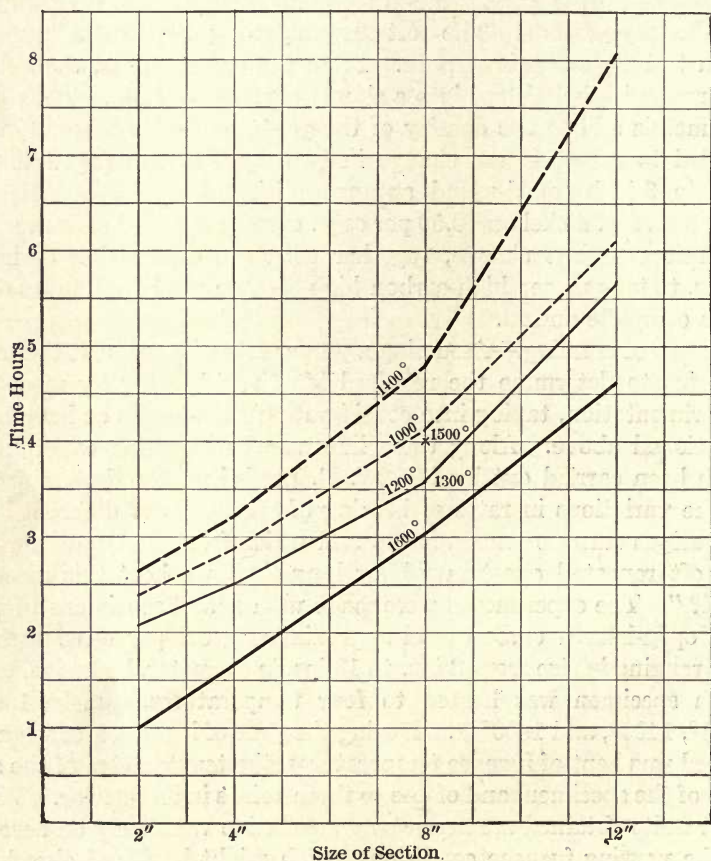


FIG. 41. Curves Derived from Rate of Heating. (Courtesy of Leeds & Northrup Co.)

for 1200° F. than for 1000° F., although it is greater for 1400° F. than for any other temperature.

"It is more difficult to account for the fact that the higher temperatures are attained more rapidly than the lower ones. This fact, however, appears to be clearly demonstrated. It may be that

the specimens received a large amount of their heat by radiation from the furnace walls. The heat transfer by radiation between two bodies at different temperatures is proportional to the difference between the fourth powers of their absolute temperatures, and so for a  $100^{\circ}$  difference in temperature between furnace wall and test specimens, at  $1600^{\circ}$  F., the heat transfer would be at a higher rate than for the same temperature difference at lower temperatures.

**3. "Relation between Surface and Interior Temperatures.—**From all of the curves, it is deduced that there is no large difference in temperature of the points inside of the specimen. This was quite surprising, as it was expected that the 12-in. specimen would show considerable differences of temperature between a point 2 ins. from the surface and the center.

"All of the runs show that the contact couple is at a higher temperature than any of the interior couples until the specimen has attained the temperature of the furnace. It cannot properly be assumed that the temperature shown by the contact couple is exactly that of the surface of the specimen.

"When the contact couple attains the furnace temperature, all parts of the specimen have also attained that temperature. This suggests a practical method of using contact couples in conjunction with furnace couples, namely, by means of the furnace couple the furnace should be held at the temperature at which it is desired to treat the specimen, and the contact couple should then be used to determine when the specimen has assumed the desired temperature.

**4. "Contact Couple Shows Time of Transformation.—**The curves (not given here) showing the heating of the 12-in. and 8-in. specimens to  $1400^{\circ}$  and  $1600^{\circ}$  F. show that the transformation point is clearly shown by the couples inside of the specimen, and that it is also shown by the contact couple. The interior couples show, with approximate correctness, the temperature at which the transformation takes place. The contact couple shows a corresponding flexure in its curvature, at the same time as the interior couples, though not at the same temperature." The close correspondence in time between the flexures of the contact couple and the interior couples points to what Mr. Leeds believes is an important new method of determining when a piece of steel has been heated through its transformation point.

**Rate of Cooling.—**We know from our study of the previous chapters that in hypo-eutectoid steels the solid solution rejects the excess ferrite upon cooling through the transformation range. This

ferrite will form either a network around the grains of solid solution or pearlite, or will coalesce into irregular masses, the same being dependent upon the rate of cooling. A moderately slow cooling will develop the cellular or network structure without breaking it up. A very slow cooling will break up the network structure, giving ample time for the ferrite to coalesce into large masses. The slower the cooling through the transformation ranges, the greater also will be the size of the grains.

**Effect of Cooling.**—The effect of the varied rate of cooling is illustrated in the photomicrographs of a 0.45 per cent. carbon steel



FIG. 42.—Network Structure, 0.45 per cent. Carbon Steel.  $\times 100$ . (Bullens.)

shown in Figs. 42, 43 and 44, all taken at the same magnification. All three pieces were heated to a temperature somewhat in excess of the full annealing temperature. The steel of Fig. 42 was cooled quite rapidly (air-cooled); that of Fig. 43 was cooled rapidly through the upper part of the transformation range, but slowly through the lower critical range; that of Fig. 44 was cooled with the furnace. Thus we have the network structure in the first case, showing a comparatively small grain-size. In the second instance the network is coarse and the pearlite is fairly well developed. A very slow cooling, as in the third case, has resulted in a coalescence of the ferrite into large grains, intermingling with the coarse pearlite. The ferrite in all three photomicrographs is represented by the white constituent.



Some very interesting facts might be drawn from a study of these photomicrographs in comparison with those previously mentioned in the series of Figs. 27 to 31, and Figs. 32 to 36.

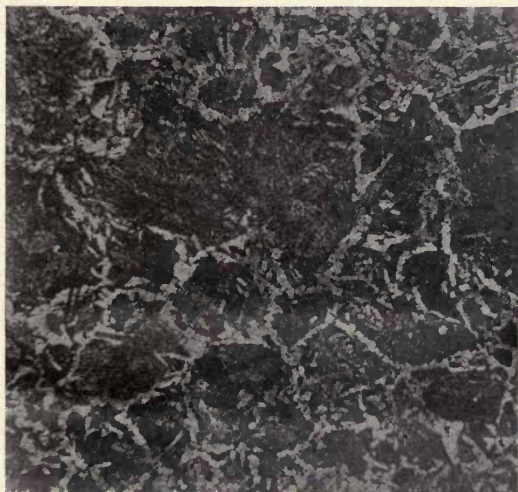


FIG. 43.—Coarse Network Structure, 0.45 per cent. Carbon Steel.  $\times 100$ .  
(Bullens.)

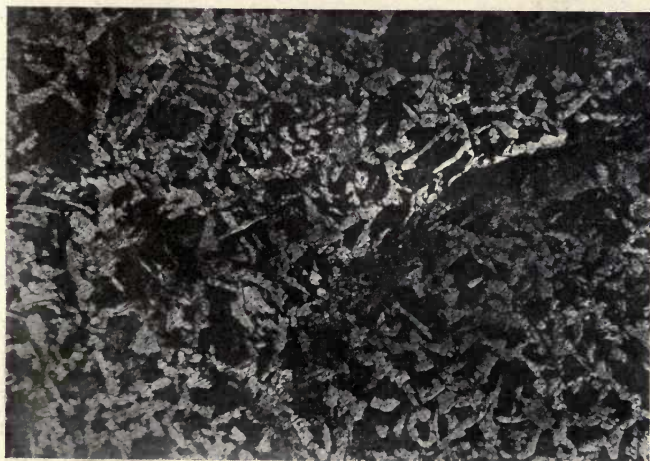


FIG. 44.—Coalesced Ferrite and Pearlite, 0.45 per cent. Carbon Steel.  $\times 100$ .  
(Bullens.)

**Effect of the Rate of Cooling upon the Pearlite.**—Not only does the rate of cooling from the annealing temperature have a very great effect upon the network and grain structure, but also upon the characteristics of the pearlitic constituents of the steel. The rate of

MICROSTRUCTURE.	SEGREGATION STAGES.	MECHANICAL PROPERTIES.
	I. Sorbite or "sorbite pearlite." Cementite emulsified.	Tensile strength about 150,000 lbs. per sq. in. Elongation about 10% in 2 ins.
	II. Sorbite passing into normal pearlite. Semi-segregated cementite.	Tensile strength about 125,000 lbs. per sq. in. Elongation about 15% in 2 ins.
	III. Finely laminated pearlite.	Tensile strength about 100,000 lbs. per sq. in. Elongation about 10% in 2 ins.
	IV. Laminated pearlite. Completely segregated cementite.	Tensile strength about 85,000 lbs. per sq. in. Elongation about 8% in 2 ins.
	V. Laminated pearlite passing into massive pearlite. Cementite and ferrite each coagulating	Tensile strength about 75,000 lbs. per sq. in. Elongation about 5% in 2 ins.

Cementite—white  
Ferrite—black.

FIG. 45.—Pearlitic Development.

cooling through the lower critical range, at which the transformation of the solid solution into pearlite is effected, will so change the arrangement of the ferrite and cementite constituents of the pearlite that widely varying physical results may be obtained in this manner.



As we will explain later, the austenite does not directly change into pearlite, but passes through a series of transition constituents with varying physical properties. The majority of these, however, are not retained in the steel through methods of cooling other than quenching (which may or not be followed by a reheating), so that we need consider only the very last transition, sorbite. This component sorbite represents the last stage of the transition austenite to pearlite, and in which the individual particles of ferrite and cementite are just on the verge of coalescing. Sorbite, or sorbitic-pearlite, is noted for its combination of high tensile strength (i.e., in comparison with the later phases of pearlite) and ductility. Sorbite is generally formed by air cooling through the lower critical range, and is shown in Fig. 45. This figure also illustrates the different phases of the pearlite, together with their approximate physical characteristics. From this it will be evident that the rate of cooling must necessarily have a great influence upon the physical properties of the slowly cooled or annealed steel, and that the operation must be adjusted accordingly.

**Definite Cooling.**—Thus we see that having obtained the permanent release of all internal strains and stresses and brought about the formation of an entirely new grain-size and structure by means of proper heating, it now remains to adjust the physical properties by means of regulating the rate of cooling. In general, there are three methods of cooling as used in the annealing process. These are: (1) Cooling in and with the furnace, (2) removing the steel from the furnace and covering with some blanketing substance such as lime, sand, ashes, etc., (3) cooling in air. Cooling by means of quenching is not a true annealing operation, and will therefore be considered under the subject of "Hardening."

**Furnace Cooling.**—Cooling in and with the furnace will generally give the slowest cooling of the steel which is possible if the furnace is of heavy construction and can be tightly closed. Furnace cooling will give a maximum "softness" and ductility—that is, the tensile strength and elastic limit will be at a minimum, and the elongation and reduction of area will be large. Steel in this condition will be in a suitable condition for ordinary machining, and will also have the quality of resisting a small number of severe distortions.

**Slow Cooling.**—In cases where the objects are of large size, an approximation of furnace cooling may be obtained by removing the steel from the furnace and covering with some blanketing substance and slow conductor of heat such as lime, sand or ashes. This will



also permit the recharging of the furnace for another heat without loss of time.

**Pit Annealing.**—Where a large tonnage of steel must be annealed, a pit lined with brick or concrete and suitably fitted with cover plates is sometimes made. The hot steel is immediately delivered from the annealing furnace to the pit and covered with ashes. Cooling by this method of pit-annealing is often slower than cooling in the furnace itself if the latter is not properly constructed so that no cold air can find its way in.

**Size of Object.**—It is readily realized that the size of the object has a great bearing upon the rate of cooling. Under the same conditions a smaller object will cool much more rapidly and will therefore be harder and less ductile than a piece of considerable size. The rate of cooling must therefore be proportioned to the size of the object.

**Air Cooling.**—If the steel is removed from the furnace and allowed to cool in air the physical properties will be proportional to the dimensions of the piece and also dependent upon the carbon content. Thin objects and those with high carbon content cannot stand so rapid a cooling as thick and low carbon ones, lest their ductility be too greatly sacrificed. In this regard the American Society for Testing Materials recommends the following: "Thick objects with less than 0.50 per cent. of carbon may be cooled completely in air, of course protected from rain or snow. Objects with 0.50 per cent. of carbon or more, and thin objects with from 0.30 to 0.50 per cent. of carbon may be cooled in air if their cooling is somewhat retarded, as, for instance, by massing them together, as happens in the case of rails." This more rapid cooling will give great strength and high elastic limit, but less ductility.

**Combination Air and Furnace Cooling.**—Besides the regular air or furnace cooling there are a number of different combinations of the two which have given great success in innumerable cases. We will give them briefly as follows:

1. Heat to slightly over  $Ac_3$ , air cool to just over  $Ar_1$ , return to a furnace which is held at that temperature (about  $1350^{\circ}$  F.), heat until uniform, and then cool slowly. The latter heating should not be any longer than is possible. This method will tend to prevent the formation of large amounts of free ferrite, but will affect the pearlite, as there will be slow cooling through the  $Ar_1$  range.

2. Heat to slightly over the  $Ac_3$  range, air cool to just under the  $Ar_1$  range, return to a furnace and heat at  $1350^{\circ}$  F. and slow cool.

This method will effect a greater "toughening" if the temperature has not been prolonged too greatly at the second heating.

3. Heat to slightly above  $Ac_3$ , air cool to below  $Ar_1$ , return to a furnace heated at a temperature slightly below  $Ar_1$  (about  $1200^{\circ}$  to  $1250^{\circ}$  F.), hold at this temperature until uniformly heated, and slow cool. In fact, the last cooling may be made in the air if desired, as there will be little or no change in cooling from under the lower critical range.

**Fine Grain Annealing.**—Of the three special methods given, the third is the preferable, as well as the most uniform and certain in results. By permitting the steel to air cool to a temperature below the lowest transformation, advantage is taken of any "hardening effect" or retardation in the transformation of austenite into a conglomerate of pearlite and ferrite. This effect will increase with the percentage of carbon and the smaller the size of the piece. The reheating to a temperature below the lower critical range, if not prolonged, will neither change the grain size nor allow of the coalescing of the excess ferrite or of the individual constituents of the pearlite, but will form a mass of irresolvable and intermixed pearlite and ferrite known as "sorbite." At the same time, however, it will give the maximum combination of large ductility, good strength and excellent machining properties. This method is of particular value in the annealing of tool steels, in which it has given most excellent results.

The main objection to both of the other two methods is that a varying duration of heating above the lower critical range will cause corresponding changes in the results, so that no absolutely definite result capable of commercial duplication can be obtained. The methods, however, find many applications in a general way, particularly in steels of medium carbon content which have been severely stressed by previous mechanical elaboration. The second method especially will give the advantage of having had a double heating through the lower critical range (besides the minimum grain-size conferred by fairly rapid cooling from the upper critical range), and thus breaking up the previous structure.

**Double Annealing.**—The next variable which may be used is that of heating to a temperature considerably in excess of the upper critical range, air cooling to under the lower critical range, and reheating to slightly above the lower or upper critical range. As an example of this the author will cite a case which was successfully solved by this method. Certain medium-carbon steel plates



had been finished at a temperature considerably under the proper temperature for hot-rolling and thus had been considerably stressed—in fact, the ordinary annealing method would not relieve this condition. The plates were put in a furnace with a car-bottom, heated thoroughly at about 1700° F. (that is, considerably over the Ac3 range), air cooled until black, and then reheated and slow cooled from a temperature slightly over the lower critical range. The laminations occasioned by the rolling were entirely eliminated by the high temperature, and their reformation prevented by the rapid cooling in air. The second anneal then thoroughly softened the steel and put it in good condition for the following forming operations. This steel might, of course, have been reannealed at the Ac3 range (instead of the Ac1 range) and an even better product obtained.

**Tool Steel Annealing.**—The annealing of hypo-eutectoid tool steel may be broadly grouped under two headings, dependent upon the initial condition of the steel and upon the results desired. Tool steel which has been carefully hammered is undoubtedly strengthened by this mechanical elaboration; a full annealing—that is, heating at a temperature over the critical range—will entirely destroy the results of the forging operation. If it is therefore desired simply to anneal the steel in order to put it in suitable condition for machine work—that is, to soften it and at the same time to retain the beneficial effects of the forging—the annealing operation should be carried out at a temperature less than that of the critical range, or in the neighborhood of 1200° to 1250° F. On the other hand, if it is desired to obtain the finest grain size possible, the maximum softness, and to entirely eliminate any previous heating or forging work, the annealing should be carried out at a temperature slightly over that of the critical range, or in the neighborhood of 1400° F., dependent upon the composition of the steel in question.

**Protection of Steel.**—One of the vital points in obtaining a satisfactory steel after annealing is the protection of its surface. Steel when heated beyond a low-red heat exhibits a great tendency to oxidize or scale, this action increasing, in the presence of oxygen, with the temperature and the length of time involved. This condition will exist in furnaces operated so as to produce sharp heats, instead of soft, slightly hazy, reducing atmospheres. Decarburization to a depth of  $\frac{1}{4}$  to  $\frac{1}{2}$  inch is not a rare occurrence where improper combustion and heat application is the rule. If, due to poor furnace design and worse operation, such conditions do exist, in order to



produce a clean surface it will be necessary to protect the exposed surface of the steel in some manner. Tool steel is often annealed by placing in a tube, packing carefully with charcoal, and then closing the ends of the tube with caps or luting with clay.

On the other hand, the prevention of oxidation or the scaling of the metal during the heating process is a simple thing with the *proper furnace design and operation*. Assuming such a design, if the furnace is operated so as to produce soft, hazy heats such as we have previously mentioned, there should be no occasion for packing the steel in charcoal or other such substances. This statement is made not as one of theory, but as one of actual practice. Under-fired furnaces are being run to-day on brass cartridge case work in which there is less oxidation and decolorization of the metal than in other furnaces in which the metal is packed in charcoal; not only is a better product being obtained, but at less operating cost.

**Box-Annealing.**—For the protection of larger masses or a number of smaller pieces, “box-annealing” is often resorted to. This particularly applies to cases where a finished surface must not be injured. The steel is placed in a rectangular pot or box made of cast iron or of plates riveted together. This box may or not be lined with some refractory substance such as silica brick. The metal is then carefully packed with some material such as ground mica, sand, charcoal, charred bone or leather, lime, etc. If the steel is low in carbon a carbonaceous or carbon monoxide generating substance must not be used, for a slight case-hardening action would take place. In the case of higher carbon steels, and especially of tool steels, reducing agents may be used, although it is better to mix the charcoal with clean ashes. Sand and ground mica are probably the most satisfactory of the simple non-reducing, refractory materials. The cover is then placed on the box and the box with its contents is charged into the furnace and given the proper degree and duration of heating. The box should be raised from the floor of the furnace so that the hot gases may have opportunity for circulation around it. When properly heated throughout, the box may be removed from the furnace and allowed to cool to atmospheric temperature.

**Stead's Brittleness.**—We have previously stated that practically no change occurs below the Ac1 range if no previous hardening of the steel has taken place. The one exception is that of very low-carbon steels and is due to the fact that steels very low in carbon behave more like pure or carbonless iron, there being but small percentages of cementite (and therefore pearlite) to influence the grain-size.

Upon heating such steels through the upper part of zone 1a (refer to diagram in Fig. 13), a distinct coarsening of the ferrite grains occurs, this being a function of time as well as of temperature. Steels of such carbon held at say 1100° F. for a considerable length of time will develop such coarsening of grain-size as to make the steel unfit for commercial use if any degree of strength is required. This phenomenon is known as "Stead's Brittleness." With steels of greater carbon content the increased pearlite so operates upon the molecular structure of the steel that practically no change occurs until the Ac1 range is reached.

#### ANNEALING HYPER-EUTECTOID STEELS

**Critical Ranges.**—Strictly speaking, hyper-eutectoid steels have two critical ranges: the A 1.2.3, at which—on heating—the pearlite changes into the solid solution; and the A cm range, at which—on heating—there is the final solution of the excess cementite—just as in hypo-eutectoid steels the Ac3 range represents the solution of the last of the excess ferrite. However, on account of the relatively small proportion of free cementite in the ordinary hyper-eutectoid steels, and also because there is a large increase in grain-size upon heating to the Ac.cm range—the temperature position of the latter increasing very rapidly with increase in the carbon content—the Ac.cm range requires but little practical consideration and the majority of the annealing operations are more intimately connected with the principal critical range Ac 1.2.3.

**Commercial Annealing.**—Similarly to hypo-eutectoid steels, the annealing of high-carbon steels may have for its object any or all of the following factors: (1) the release of internal strains and stresses set up by previous operations, (2) the softening of the steel to place it in a suitable condition for machining, (3) the entire change of structure.

The first item may be accomplished by a simple reheating at temperatures below those of the critical range. The second and third items are more complex in their solution, as the form in which the excess cementite may exist is one of the governing factors.

If the mass of the steel is in the sorbitic state, as may generally be expected in the usual tool steel, satisfactory results (the softening of the steel for machining, and relieving the internal strains) may be obtained by an annealing at a temperature slightly *under* that of the principal critical range, or at about 1250° to 1300° F. This heating



should not be prolonged for such length of time as may cause the excess cementite to coagulate, but only until the steel has been thoroughly and uniformly heated throughout.

On the other hand, if it is desired to obtain the complete change of structure, and to refine the grain (previously coarse), it will be necessary to heat to a temperature at least in excess of the Ac 1.2.3 range (about 1340° F.). For steels with a carbon content approximating 0.9 per cent., such heating will accomplish the complete change of structure and give the finest grain-size obtainable through annealing. For steels with a carbon content considerably in excess of the eutectoid ratio the annealing may be done at similar temperatures, provided, however, that the excess cementite is more or less in solution in the sorbite.

Incidentally, if the condition stated under (3) is desired, and it will warrant the expense, the best method is first to oil quench from a temperature somewhat over the Ac 1.2.3 range, and subsequently anneal at a temperature just below that range.

**Normalizing.**—If the steel to be annealed has the free cementite existing as network or spines, which would make the steel difficult of machining, annealing at the usual temperatures (Ac 1.2.3) will not affect this cementite: it will simply refine the ground-mass. In order to eliminate this free cementite, it will be necessary first to normalize or quench the steel from a temperature above that of the Ac.cm range. That is, air cooling from a temperature of say 1750° or 1800° F. will not permit of the reformation of coagulated cementite. The second annealing may then be carried out at a temperature of 1375° with the refining of the grain size and complete softening of the steel as a whole; this second heating should be just as short as possible in order to prevent the reformation of the free cementite.

**Spheroidizing the Cementite.**—The above method may be further modified by reheating to a temperature slightly under the lower critical range instead of over it. The objection to this is that the steel will not be refined, but will possess the large grain size characteristic of the high temperature. On the other hand, the lower annealing temperature will entirely prevent the formation of the free cementite as either spines or as a network. Instead, it will be found that the excess cementite will be thrown out, under these conditions, as little nodules or "spheroids" if the reheating temperature is just about at the end of the lower critical range; or, under certain conditions, the whole mass of the steel may be called "granular," if such



a term is permissible. Further reference to this spheroidal formation of cementite, as obtained by a double "quenching," is given under Chapter VII. Spheroidal cementite in annealed steels may also be obtained by very slow cooling through the end of the Ar<sub>1</sub> transformation: cementite in this condition is a great help in the machining of high-carbon steels.

## CHAPTER IV

### HARDENING

**Hardening.**—Fundamentally, the operation of hardening involves two operations of change in temperature: heating and cooling. The function of the heating is (1) to obtain the best refinement, and (2) to obtain the formation of the “hard” constituents of the steel. Having done this, the steel must then be held in this condition by very rapid cooling—that is, by quenching in some medium such as water or oil. Associated with both the heating and rapid cooling there must be as great a degree of uniformity as is possible.

**Changes on Heating.**—Steel, when properly hardened, should show no trace of the original structure, such as coarse grain size, network, unabsorbed ferrite (in hypo-eutectoid steels), or any other peculiarities of untreated steel. If such are present in the hardened steel it goes to prove that the operation was not properly carried out. Further, if the structure of the steel has not been suitably changed or developed by the heating operation, it most assuredly will not be altered for the better by subsequent quenching. The most that such quenching can do is to retain the characteristics which the heating has developed.

An attempt has been made graphically to illustrate these facts in the chart in Fig. 46. Column I (at the left) represents a normal, 0.4 per cent. carbon, pearlitic steel (at the bottom of the column), and the structural changes taking place in that steel as it is progressively heated through and beyond the critical ranges. For the present it is assumed that the structure and micrographic constituents obtained by heating to various temperatures, such as A to E, may be retained by quenching, as illustrated by columns II to VI.

Thus heating to a temperature A, under that of the lower critical range, will produce no change in the original steel, which consists of pearlite (the cross-hatched circles) and ferrite (the black area). The quenching likewise will produce no change, as is illustrated by Column II.

Heating to a temperature B, slightly over the lower critical range, will change the pearlite to the solid solution (represented by

the dotted area), but without affecting the free ferrite. Quenching, column III, will therefore produce a semi-hardened steel—since the solid solution is the “hard” constituent—with a refinement of the “ground-mass” (the original pearlite) only.

Heating to a temperature C, between the lower and upper critical ranges, will effect a progressive absorption by the solid solution of

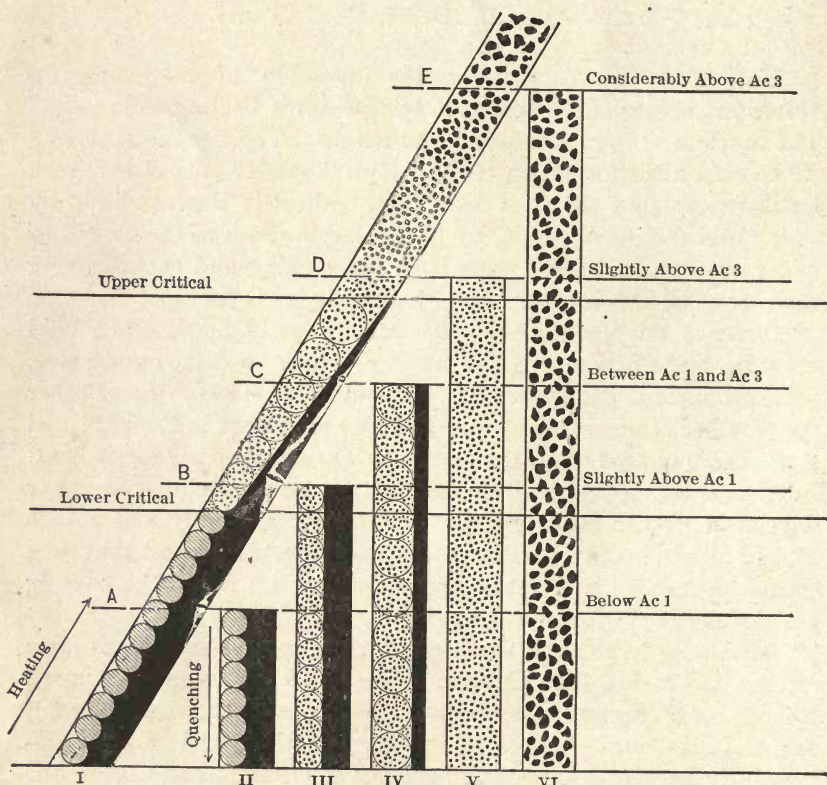


FIG. 46.—Changes in a 0.4 per cent. Carbon Steel on Heating and Quenching.

the remaining free ferrite. Quenching, column IV, will therefore produce a “harder” steel than in case III, but nevertheless without complete refinement of the steel as a whole.

Heating to a temperature D, slightly over the upper critical range, if prolonged for a length of time sufficient to effect complete diffusion and equalization, will entirely refine the steel, giving it the smallest grain size possible. Quenching, column V, will retain this condition and give the maximum hardness possible.



Heating to a temperature E, considerably over that of the upper critical range, will tend to increase the grain size; and quenching, column VI, will retain this condition, giving a more brittle steel.

**Relation of Hardening to Annealing.**—Thus it will be seen that during the *heating* operation the changes taking place in the microscopic constituents and the structure as a whole are similar in both hardening and annealing. The main difference in the final results of the two processes is due to the rate of cooling through the critical ranges, and, therefore, upon the nature of the micro-constituents which are thereby retained in the steel when cold.

The effect of slow cooling through the critical ranges, which is characteristic of true annealing, has been discussed; in brief it may be said that the austenite or solid solution shifts its carbon content through generating pro-eutectoid ferrite (or cementite) to the eutectoid ratio of about 0.85 to 0.9 per cent. carbon, and then transforms with increase of volume at Ar<sub>1</sub> into pearlite, with which the ejected ferrite (or cementite) remains mixed. This change or decomposition of the austenite, however, does not take place suddenly or spasmodically, but develops by stages; and that these intermediary stages between austenite and its final constituents may be recognized and identified under the microscope as martensite, troostite, osmondite and sorbite is generally accepted. Hardening is but the result of obstructing this transition, thereby retaining in the steel the "hard" austenite or its early decomposition products martensite or troostite.

**Austenite.**—Austenite is only obtained with difficulty in the ordinary carbon steels, and even then is usually decomposed in part into martensite. The two agents<sup>1</sup>—rapid cooling and carbon—tending to obstruct this transition must be grouped in suitable proportions—that is, the carbon content must be high, and the cooling take place with extreme rapidity. With about 1.5 per cent. carbon steel, such as is generally used in corrugating and roll-turning tools, when quenched in brine or very cold water from about 1400° F., about one-half of the austenite will remain unaltered. When the carbon is about 1.1 per cent.—which may be regarded as about the minimum limit, although the author has succeeded in obtaining some austenite with water-quenched 0.9 per cent. carbon steel—the cooling must be done in iced solutions from a temperature of 1800° F. or more.

<sup>1</sup> Alloys are also obstructing agents in the sense that, if present in the proper amount, they lower the temperature at which the transition will commence.

The hardness of austenite, as preserved in hardened high-carbon steels, does not fall very far short of that of the accompanying martensite, probably because the austenite is partly transformed into martensite in cooling. On the whole, however, austenite may be regarded as being considerably softer than martensite, and also much tougher; the austenite as obtained in high manganese and high nickel steels is but moderately hard.

**Martensite.**—Martensite is the chief characteristic constituent of hardened carbon steels when cooled rapidly in water from a temperature above the A3 range. In very high-carbon steels, rapidly



FIG. 47.—Martensite.  $\times 75$ . (Ordnance Dept.)

cooled, the martensite is associated with austenite. In the lower carbon steels hardened in water, in high-carbon steels hardened in oil, or in thick pieces of high-carbon steel hardened in water, martensite is associated with troostite and with some pro-eutectoid ferrite or cementite.

Of the transition constituents—austenite to pearlite—martensite is the hardest and also the most brittle, having extremely high tensile strength with little or no ductility. Microscopically martensite is characterized by a needle-like structure as is shown in Fig. 47.

**Troostite.**—Troostite is obtained by cooling through the transformation range at an intermediate rate, as in small pieces of steel



when quenched in oil, or quenched in water from the middle of the transformation range, or in the center of larger pieces quenched in water from above the critical range. The early appearance of troostite in tool steel is shown in Fig. 48.

The hardness of troostite is intermediate between that of the martensitic and pearlitic state corresponding to the carbon content of the specimen. In general, the hardness increases, the elastic limit rises, and the ductility decreases, as the carbon content increases.

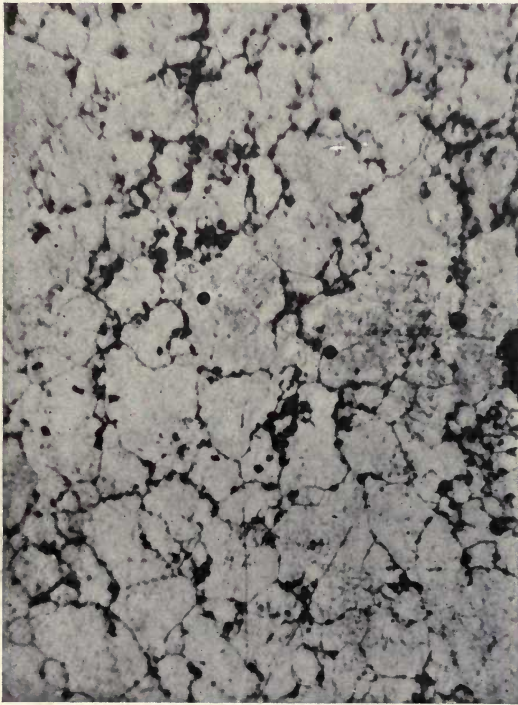


FIG. 48.—Troostite (Dark) in Hardened Carbon Tool Steel.  $\times 100$ . (Bullens.)

**Sorbite.**—Sorbite, when obtained by hardening, is ill defined and almost amorphous; it is softer than troostite for a given carbon content. Dependent upon the carbon content, sorbite may be obtained by quenching small pieces of steel in oil or in molten lead, or even by air-cooling them; or it may be obtained by quenching in water from just above the bottom of the  $A_{r1}$  range. Sorbite, and to some extent, troostite, are more characteristic of tempered



steels than of hardened steels. The transformation of troostite into troosto-sorbite is shown in Fig. 49.

**Temperature for Hardening.**—As a general rule, hardening is carried out from a temperature of about 50° F. above the line A3–A2.3–A1.2.3 in Fig. 13. This is done to obtain the best refinement of the steel as well as the maximum hardening effect. Rapid cooling of medium and low-carbon steels from a temperature just above the

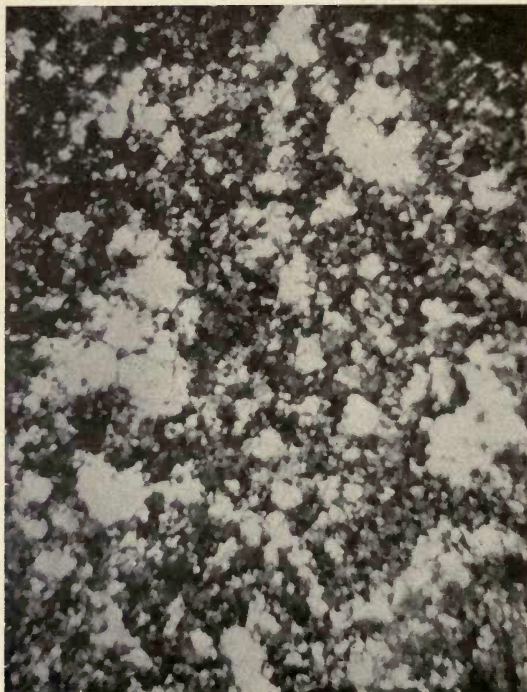


FIG. 49.—Trooste-Sorbite (Dark),  $\times 100$ . (Bullens.)

bottom of the critical range A1, will not bring out the maximum hardening effect. The general temperatures most applicable for individual steels are given in subsequent chapters.

When the maximum results, both as affecting the structure and also the physical results, are to be obtained, experiments should be made to determine exactly how far over the critical range the steel should be taken. In some steels it will be found that approximately 50° F. will accomplish this purpose; in others it may be necessary

to raise the temperature to even 150° F. or more. This effect will also be influenced by the size of the piece to be hardened, as will be shown under "Tool Steel."

**Heating for Hardening.**—The general rules for heating for hardening may be simply stated, but their fullest comprehension and application may be obtained only in the light of experience. This heating requires much more care than heating for annealing (if such be possible), on account of the diametrically opposite functions which are indicative of the two operations. Heating for annealing is followed by slow cooling and the gradual release of all stresses and strains: heating for hardening is followed by the most severe test to which steel can be put—very rapid cooling, accompanied by the setting up of a condition of stress and strain. In general, we may say that the heating for hardening should be *slow, uniform, and thorough*, and to the *lowest temperature* which will give the desired results.

Non-uniformity in heating must of necessity result in lack of uniformity in cooling, which in turn is the genesis of most of the troubles in the hardening process. Hardening cracks are more often the result of uneven heating than of a defect in the steel. Heating requires time and care. The peculiarities of each steel and article must be thoughtfully studied; experiments must be made; and the clear judgment of experience applied to each individual case. It has been well said that "Steel is mercurial and delicately responsive to heat; its records appear in its own structure."

**Lowest Quenching Temperature the Best.**—The lowest heat which will give the results desired should always be used in hardening. This point can be brought home in no better way than to give the results of two tests made which illustrate exactly this principle. Two automobile gears were made from the same bar, by the same man, and in all other ways as nearly alike as possible. The tests were made by a disinterested third party.

Number 1 was quenched in oil from 1450° F., annealed at 1400°, hardened in oil from 1450°, and tempered at 475° in oil. It gave a sclerescope hardness of 76 to 78. It withstood 48 blows of a 10-lb. hammer dropping 30 ins. before a tooth could be broken out, or 8 blows of a 10-lb. hammer dropping 48 ins.

Number 2 was quenched in oil from 1400°, which was just over the critical range, and determined by when the magnet "let go." It was annealed at just under that temperature, followed by hardening in oil from 1400° and tempering in oil at 475°. The



hardness was the same as with No. 1. In this case, however, it required 200 blows of the 10-lb. hammer falling 30 ins., or 78 blows with a fall of 48 ins.

The effect of the increase of only  $50^{\circ}$  in the hardening temperature is self-evident: it meant a difference in efficiency in the ratio of 48 to 200.

**Temperature of Quenching.**—It is not only the uniformity of heating of the steel object which is necessary for uniform and proper hardening, but also—and equally important—the uniformity of temperature of the piece at the moment of quenching. A piece of steel may be properly heated at the moment previous to its withdrawal from the furnace; but that same piece may have wide differences of temperatures in different parts of the mass at the moment of quenching. Non-uniformity of heat saturation at the latter instant must inevitably result in non-uniformity of hardening—with the attendant possibility of warping, cracking and similar features. Whether or not the indirect cause of such a condition is due to the shape and size of the object or to the method of handling the stock between the furnace and bath is immaterial as far as the basic principle outlined above is concerned. These are but a manifestation of the ever-present “personal element.”

**Overheating.**—Overheating is probably one of the most common sins of the hardening shop. Unfortunately, many “practical” men still believe in the efficacy of high temperatures for greater hardening effect. Although this may—to a very limited extent—be true, the weakening of the steel by the increase in grain size and greater hardening strains as obtained by high temperatures more than offset the questionable production of greater hardness. Fully 80 per cent. of the complaints of “bad steel” which have been brought to the author’s attention have been the direct result of overheating. Both theory and practice support the old rule that “the lowest heat which will give the desired results is the best heat.”

**The Magnet in Hardening.**—It will be recalled that steel becomes non-magnetic (for all practical purposes) in passing through and beyond those temperatures represented by the heavy black line in Fig. 50. For steels with about 0.35 per cent. carbon and upwards this temperature line also corresponds to the best refinement of the steel in heating. We therefore have a very simple and practical means of determining the proper temperatures for hardening such steels. All that is necessary is to apply an ordinary horse-shoe magnet, suspended from a suitable rod, against the hot steel. When



the correct hardening temperature has been reached there will be no attraction between the magnet and the steel. For steels with less than about 0.3 per cent. carbon the rise in temperature between the  $Ac_2$  and  $Ac_3$  ranges may be estimated and the steel hardened when it has reached the latter temperature. It will be found that the use

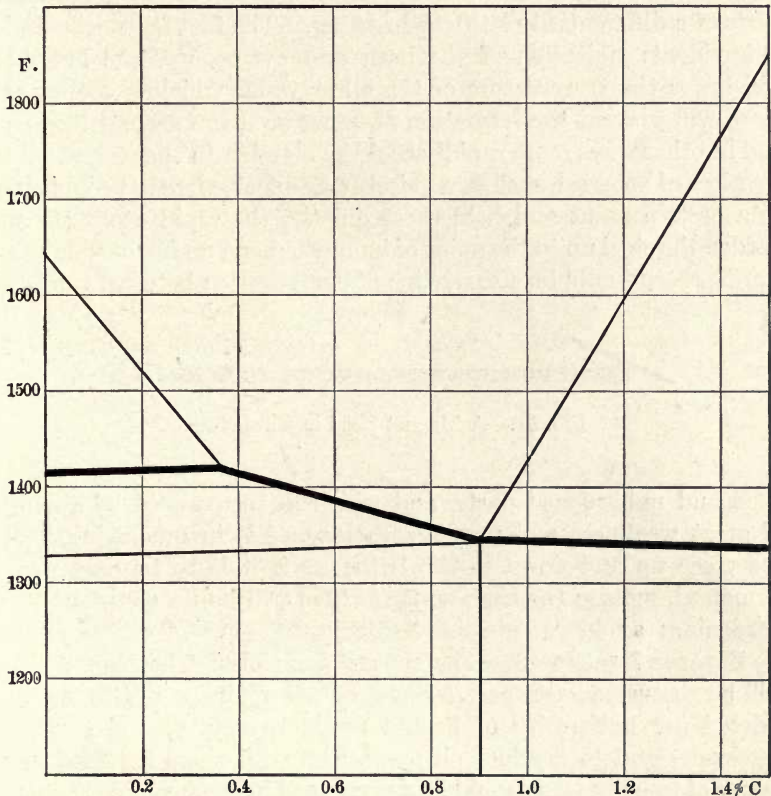


FIG. 50.—Carbon-iron Diagram Showing Temperatures at which Ordinary Carbon Steel Loses Its Magnetism on Heating.

of the magnet will be of great value to those not having the proper pyrometer control over their heating operations and who have to depend entirely upon the eye for gauging such. An instrument more convenient for this purpose than the ordinary magnet is made by magnetizing a small, elongated, diamond-shaped piece of steel,

and supported between two pins in the end of a forked rod, as is shown in Fig. 51.

**Motion during Hardening.**—When a piece of steel is quenched, movement should be given to the steel, to the quenching medium, or to both. This is for two reasons: (1) in order to cool the steel as rapidly as possible, and (2) to break up any tendency toward the formation of a distinct line between the hardened and unhardened parts of a differentially hardened forging. The first factor should be self-evident: agitation of the bath or movement of the hot steel will lower the temperature of the oil or water which is cooling the steel, will prevent the formation of vapor or steam around the steel, and in other ways more rapidly cool the metal. In the second place, if a piece of hot steel, such as a chisel or die-block, were to be immersed to a certain point and held there quietly, the rapid cooling would harden the steel up to the point of immersion and no further; in other words, there would be a sharp line of demarkation between the hard-

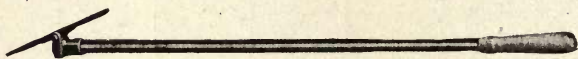


FIG. 51.—A Magnet Used in Hardening.

ened and unhardened parts, and which in turn would be a source of great weakness and possible fracture. So, in quenching, move the piece up and down in the bath; or if it is to be only partly immersed, agitate the bath so that there will be no distinct line of hardening: avoid straight-line hardening.

**Furnace Equipment.**—The general principles of heat application will be discussed elsewhere. Some of the main points to be considered are uniformity of heated product, quality, and economic efficiency, and to conduct all operations with these in view. The material to be heated should be so arranged in the furnace that there is ample room for the circulation of the heat through the mass. The furnace should be so designed as to suit the class of work to be heated, and so operated that the heat shall be evenly distributed and of the same temperature from floor to roof and side to side. Only under special circumstances, such as in connection with automatic furnaces, is it desirable to operate the furnace at a temperature higher than the maximum temperature desired in the steel.

**The Human Element and Basic Heat Treatment Conditions.**—What is it or who is it that determines when the charge in the cham-



ber is saturated with heat to the temperature indicated by the pyrometer?

What determines the manner in which the charge is placed in the furnace and the room for circulation throughout the mass?

What determines when the bottom and center of the mass are at the same temperature as the top and outside?

What regulates the flow and composition of gases in the chamber around the stock and the discharge of heat from the chamber?

What determines if each piece is heated like every other piece and is uniform throughout, and whether each piece goes into the quenching bath at the same temperature as all the others and at the temperature indicated by the pyrometer?

What is it that controls the flow of air into the furnace or the flow of gases from the furnace, and by so doing determines whether the atmosphere surrounding the stock is oxidizing or neutral, and whether the fuel is conserved or wasted?

These are some of the elements that affect proper heat treatment, and they are determined, not by a pyrometer nor a furnace nor by similar apparatus nor by any mechanical means, but by the same methods that govern the quality of the products of the kitchen—the judgment and skill of the operator.

**Heating Baths.**—Despite the efficiency of design of many furnaces, —and not mentioning those of poor design—their often inefficient operation has a general tendency towards non-uniformity in heating and oxidation. In the effort to solve these two problems at once—that is, to surround the object to be heated with a constant and uniform heat on all sides, and to avoid contact with the air—the application of various molten baths has come about. Chief of these heating mediums are molten lead and certain salts. On account of the operating cost and necessarily small capacity, however, their use is largely confined to the heating of tools and other articles requiring particular care, uniformity, and freedom from oxidation. The principal use for such baths, in the author's opinion, *should be* for the retention of a bright surface on the metal after hardening, and not for uniformity in heating; any furnace, properly designed for the work in hand, heated with the right fuel, and correctly operated, should give entire uniformity of heating.

**Heating in Lead.**—Before the advent of the modern heat treatment furnace, heating in molten lead represented the most practical method of obtaining uniform heating. With a reasonable amount of care and attention the typical lead bath may be maintained at



such temperatures as the ordinary hardening operation requires and with a satisfactory degree of uniformity. Its use, however, presents many difficulties. The bath must be frequently agitated to preserve a uniform temperature. When heated to over 1200° F. lead begins to volatilize, giving off fumes which are both offensive and poisonous; suitable ventilation, such as may be obtained with a properly designed hood, should be provided to remove these fumes. Further, the bath must be covered with powdered charcoal to reduce the oxides or dross which are formed in the molten lead. Many plants will not use lead baths if temperatures greater than 1475° or 1500° F. are necessary. On account of its high specific gravity, heating in lead requires some method of holding the steel beneath the surface, as otherwise the tool would float on the surface of the bath and thus be unevenly heated. One of the most troublesome difficulties with lead baths is the tendency of the lead to stick in the holes, threads, or even to the surface of the tool when it is removed for quenching, so that uniformity of cooling is sometimes materially affected. Although this particular difficulty has been largely eliminated by the use of a paste, the trouble may simply be aggravated in case this coating has not been carefully and properly applied.

**Salt Baths.**—Many of the difficulties encountered in the use of lead for heating may be overcome by the substitution of different salts. Their lower specific gravity permits of a more uniform circulation and there is no tendency of the tool to float on the surface of the bath. At the usual temperatures used for hardening there is little or no vaporization. Although lead may prevent the steel from oxidation while the steel is being heated, as soon as the tool comes in contact with the air on removal from the lead bath, a thin film of oxide is formed; with the salt bath, on the contrary, the steel receives a thin and uniform coating of molten salt, which protects the surface of the metal.

The minimum temperature of the salt bath may be very closely estimated without the use of a pyrometer. Common table salt has a freezing-point of 1472° F., and if it should be melted with potassium chloride (freezing-point 1325° F.) or other salts, the freezing-point of the melt may be quite accurately adjusted over a wide range of temperatures. By keeping the bath very near its freezing-point by a suitable regulation of the heat, overheating of the steel may be entirely overcome. Further, if the composition of the salt bath has been so adjusted as to approximate the proper hardening temperature, when the steel is removed from the bath it may be quenched

just at the time when the salt film begins to solidify—or at exactly the correct temperature.

#### BATHS FOR QUENCHING

**General Properties of Quenching Media.**—The main thought in selecting a proper bath for quenching is the rapidity with which the heat is removed from the hot steel. This property of transference or withdrawal of heat from the solid by and to the liquid, will depend upon the specific heat of the liquid, its conductivity, viscosity and volatility. That is, the specific heat will indicate the heat-absorptive power of the liquid; the conductivity will measure its capacity for transferring the heat thus absorbed to the cooler part of the bath; the viscosity affects the motion of the liquid and thus influences the uniformity of cooling; and the volatility indicates the temperature at which the liquid will become gaseous, thus forming a vapor around the steel and preventing the quick removal of the heat from the steel. By obtaining a suitable combination of these various properties a bath giving the desired effect may be obtained.

**Temperature of the Bath.**—The continuous use of any bath for quenching will gradually and progressively raise the temperature of the liquid used. As a general rule, differences in the temperature of the bath will give rise to varying results in the actual hardening taking place—the higher the temperature of the bath, the less its cooling efficiency. This is especially noticeable with water; a change of 50° or 100° F. will often entirely alter the physical properties of the quenched steel. The effect is less marked with oils, and with some oils may be almost negligible for certain classes of work. On the whole it is decidedly better practice to maintain as nearly as possible a standard temperature in the quenching bath.

**Quenching Speed of Different Media.**—It is evident that the cooling medium used, its temperature and condition will affect the rate of cooling. Matthews<sup>1</sup> and Stagg have devoted considerable time to investigating numerous commercial media which are in use in typical hardening plants of the country at the present time. Their method was as follows: A suitable test piece was machined from a solid bar, and a hole drilled through one end to within an equal distance from each side and bottom of the test piece. Into this hole a calibrated, platinum-rhodium couple was inserted and the leads connected to a calibrated galvanometer. The test piece was then

<sup>1</sup> Matthews and Stagg, "Factors in Hardening Tool Steel," A. S. M. E., 1915.



immersed in a lead pot, and the lead pot was maintained at a temperature of 1200° F. When the couple inside the test piece was at 1200° F., and the couple in the lead pot also read 1200° F., the test piece was removed and quenched in 25 gals. of the quenching medium under consideration. At the start the quenching medium was at room temperature. The time in seconds that it took the test piece to fall from a temperature of 1200° F. to a temperature of 700° F., was noted by the aid of a stop-watch. It is clear that immersing the test piece in the quenching medium raised the temperature of the medium. The test piece was then replaced in the lead, heated to 1200° F., quenched into the medium at this higher temperature and the time again taken with the stop-watch. These operations were continued until the quenching medium, in the case of oils, had attained a temperature of about 250° F. The results obtained, time in seconds, for a fall from 1200° F. to 700° F., were plotted against the temperature of the quenching medium and a series of curves as shown in Fig. 52<sup>1</sup> were obtained.

The various curves represent the following quenching media:

W. Syracuse city water.

B. Brine.

	Sec.
1. New fish oil; average of readings from 80° to 250° F..	85
2. No. 2 lard oil.....	87
3. Prime lard oil in use two years.....	99
4. Boiled linseed oil.....	101
5. Raw linseed oil.....	102
6. New extra-bleached fish oil.....	106
7. New yellow cottonseed oil.....	107
8. New tempering oil; 60% cottonseed, 40% mineral....	122.6
9. New mineral tempering oil.....	130
10. No. 1 dark tempering oil.....	157.3
11. Special "C" oil.....	164.7

A consideration of the results is interesting. Pure water (curve W) has a fairly constant quenching rate up to a temperature of 100° F., where it begins to fall off. At 125° the slope is very marked. Brine solutions (curve B) have both a quicker rate of cooling and are more effective at higher temperatures than water. The curve does not begin to fall off seriously until a temperature in the neighborhood of 150° is reached. Where water at 70° cooled the test piece in 60 sec., the brine solutions cooled it in 55 sec.

<sup>1</sup> For the sake of brevity and clearness the numerous curves as given by Matthews and Staggs have here been grouped under one plot.



As is well known, the oils are slower in their quenching powers than water or brine solutions, but the majority of them have a much more constant rate of cooling at higher temperatures than water or brine. The curves shown in 10 and 11 are for thick viscous oils similar to cylinder oils. These curves are particularly interesting in that they have slower quenching abilities at low temperatures than at higher temperatures. A comparison of curves 2 and 3 shows the variation in quenching power of the same oil due to continued ser-

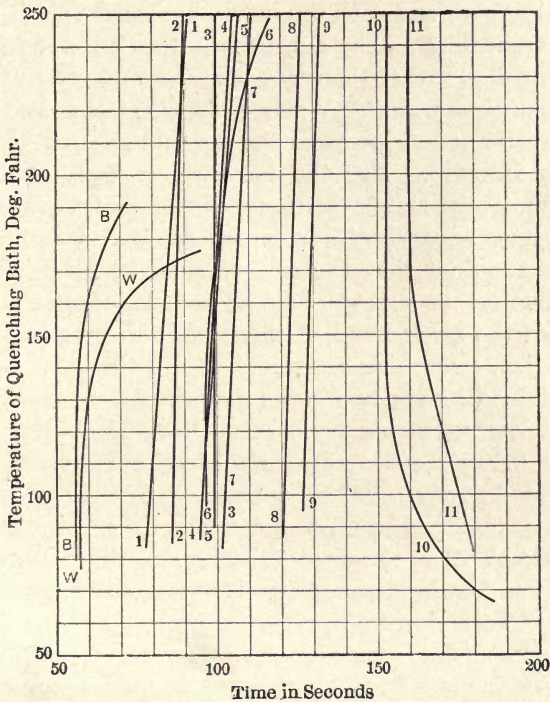


FIG. 52.—Quenching Power of Liquids.

vice. The differences in quenching rates may well account for different results from the same steel in different shops, or in the same shop due to change of oil used.

**Water Spray for Hardening.**—Water sprayed under pressure is the quickest agent for rapid cooling in common use, exceeding in its hardening qualities either brine or water baths. The main point to be noted is that there shall be sufficient volume and pressure to prevent the formation of a blanket of steam between the hot steel and the

spray. Its most common use is for such tools as sledges and others requiring a differential hardening, and for armor plate.

**Brine.**—Brine is used only in certain particular lines, such as file-hardening, for which an extremely hard surface is required. Unless the steel has been most carefully heated, and is of a proper chemical composition, quenching in brine is almost certain to crack the steel. This is particularly true of large sections, for in these the very sudden cooling of the outer surface, while the center is still hot, will set up stresses and strains which will not be relieved or equalized in the short time allowed, and with the inevitable results.

**Water Quenching.**—The author is a firm believer in the use of oil for quenching, rather than water, and would recommend its use *whenever conditions permit*. Water cools the steel more rapidly, but its more drastic action increases the internal strain and consequent liability to fracture. For the low-carbon steels, and for small and comparatively simple sections of the higher carbons, water quenching may be used without much danger. Of course in cases where it is required that the surface shall be glass-hard, or that the maximum tensile strength be obtained, water quenching is mandatory. On the other hand, if the steel is to be given a full heat treatment (i.e., quenching and toughening), the difference in hardness as obtained by the two baths may usually be nearly equalized by using a lower drawing temperature for the oil-quenched piece; that is, if a 0.40 per cent. carbon steel forging is quenched in water and toughened at say 1200° F., approximately the same static properties may be obtained by oil quenching and a subsequent reheating to say 1050° F. The principal objections to the latter method are that the lower drawing temperature is not so easily recognized by its color, nor will the dynamic properties probably be quite as high—though this last point is questionable. Generally speaking, however, oil quenching is more desirable than water quenching.

**Oil Tempering.**—The term “oil tempering,” referring to the quenching in oil, is one which has become current in the trade, so that the term, “hardening” often refers to quenching in water only, or in some medium which will give an equivalent or greater hardness. Strictly speaking, the use of “tempering” in this sense is a misnomer, for it should be used as indicative of a slight reheating or “softening” of the quenched steel.

**Special Quenching Methods.**—It often happens that especially high tensile results are desired in certain large forgings of such size and chemical composition that direct quenching in water is deemed



unwise, and yet in which it is desired to obtain as near the maximum effect of water cooling as possible. A method which has proven in a large measure successful is to use a bath of oil resting upon an equivalent or greater volume of cold water. The forgings, when heated to the proper temperature, are lowered into the oil for a few seconds and thence into the water. The oil forms a film on the surface of the steel, so that the sudden effect of the water is somewhat diminished or retarded. The rapidity of cooling may be controlled by the duration of the oil quenching. It is obvious that in using this method there must be a sufficient volume of water under the oil to prevent the formation of steam and its consequent danger.

For small tools or thin instruments such as saws, the above method may be so modified as simply to have a film of oil upon the surface of the water, the oil in this case consisting of some animal or vegetable oil. The heated tool is plunged directly and evenly through the oil film so that it enters the water with a thin coating of burnt oil which protects it from the direct action of the water and lessens the risk of fracture. The amount of oil may of course be increased as desired. The main objection to these methods is the lack of uniformity in hardening unless the operator has had more or less experience.

A method which is extensively used in some tool works is that of using a combination of water and oil quenching, that is, first plunging the tool into water until a certain amount of heat has been removed, and then transfer to the oil, where it remains until cold.

Molten lead is sometimes used as a quenching medium for small sections in which great toughness and only a moderate degree of hardness is desired. Although dependent upon the carbon content, steel subjected to this process will generally be sorbitic. Such treatment will require no further reheating.

**Other Aqueous Quenching Media.**—Hardeners, at one time or another, have tried about everything under the sun in the attempt to discover some new and wonderful quenching medium which would accomplish the phenomenal. The results, for the most part, do not warrant the addition of expensive chemicals; and if the experimenters do claim the marvelous, the "gold-brick" scheme is generally revealed by thorough investigation.

Some substances, such as lime, soap, etc., may be added to form a protective coating around the steel. Calcium chloride will raise the boiling-point of water to a considerable degree, so that the solution may be used at a temperature up to 150° or 175° F. without



danger, and at the same time give many of the advantages which oil hardening possesses. Some salts increase the hardening effect of water; others purify the water or soften it. One of the most interesting (and wonderful?) combinations which has come to the author's attention contained—by addition—ammonia, glycerine, sal-ammoniac, spirits of nitre, ammonium sulphate, alum and zinc sulphate!

**Differential Hardening.**—In certain tools, such as anvil faces, die blocks, edge tools, and the like, it is desired to obtain a very hard outer part, surface or edge, to be "backed" by a less hard and tougher steel. That is, the steel is gradually and progressively to change from extreme hardness to the opposite, or what we may term differential hardening. This phase may be obtained either by heating the whole mass of the steel—as in die blocks, or by heating only part of the article—as in chisels; in either case that part which is to have the greatest hardness is immersed or quenched. By this method the heat is gradually withdrawn from the part not immersed through that part which is being subjected to the cooling bath, so that the mass of steel as a whole will become progressively softer or tougher from the hardened face or edge to the opposite side. Precautions must be taken to avoid straight-line hardening,

**Cooling the Water Bath.**—Where water is used as the quenching medium it is customary to maintain a flow of fresh, cold water into the quenching tank so as to keep a uniform temperature and purity. Water which has been used for any length of time without renewal goes "stale" with a corresponding loss in cooling efficiency. If the cost of water is such that it is inadvisable to dispose of the overflow from the tank, the hot water may be cooled by spraying, cooling towers, etc., aerated, and then returned to the tank.

**Cooling the Oil Bath.**—The common methods for cooling the oil-quenching bath may be broadly classified as follows: (1) The circulation of cold water around, or through coils in the bath; (2) the circulation of the oil itself; (3) by the use of compressed air.

One of the simplest methods for cooling the oil when in small tanks and not too constantly used, is to place the oil tank within a larger tank, with a space of say 2 to 6 ins. between the two tanks. This space is kept filled with cold water. As in all these systems, the intake should be at the bottom of the tank, with the outlet or overflow at the top. The main objection to this method is the fact that the heat in the oil must penetrate through the walls of the tank before it can be conducted away by the water.

The next type of cooling makes use of coils or radiators placed

within the oil tank and the circulation of cold water through these pipes. These water lines are placed close against the side of the tank so that they may not interfere with the work being treated. From his own experience, the author does not feel that the radiator

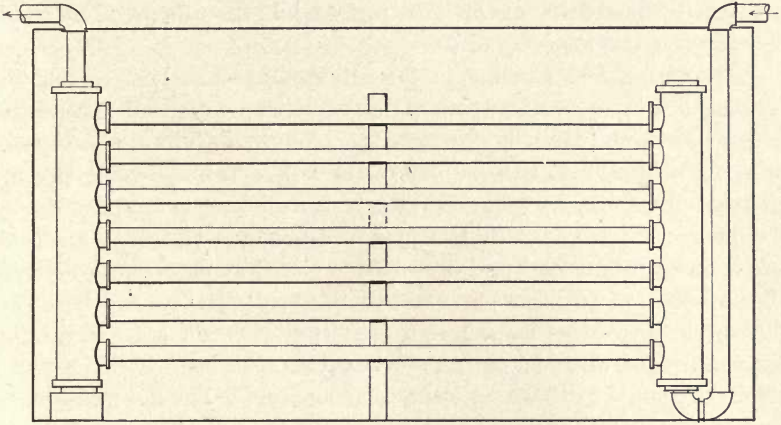


FIG. 53.—Radiator Type of Cooling System.

type as shown in Fig. 53 gives as great efficiency as the simple coil system of Fig. 54. With the difference of temperature of the oil in the bottom of the tank, as contrasted with the hotter oil at the top, it is difficult to obtain a thorough circulation of the cold water

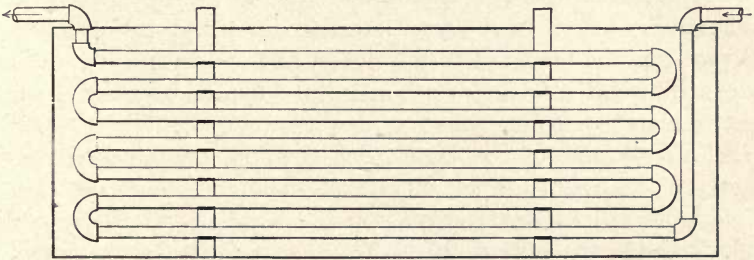


FIG. 54.—Coil Type of Cooling System.

through all sections of the radiator. Further, this same difference in temperature has the tendency towards unequal expansion of the top and bottom pipes, which may cause a leakage of water into the oil and its attendant dangers. In the coil system there is of necessity a complete circulation, together with the elimination of expansion



dangers. These pipes vary in size from about  $1\frac{1}{2}$  ins. to 3 ins. diameter; the latter size has given excellent satisfaction in a tank approximately 8 ft. wide by 16 ft. long and with a working capacity of about 8000 gals. of oil. Guide strips should be placed at intervals along the coils—from top to bottom—to prevent any articles from catching against the pipes while the quenched material is being raised out of the tank.

**Circulation and Cooling of the Oil Itself.**—The best results for keeping down the temperature of the oil bath are undoubtedly to be had when the oil itself is circulated. The circulation is continually bringing cold oil into the vicinity of the hot metal, removing the hot oil from the tank, as well as giving a more uniform temperature to the bath as a whole. In the previous systems the heat must be taken away by gradual and progressive transference from the region of the hot steel towards the sides of the tank, and at the best is a slow procedure—this is assuming that the oil is not kept in motion by compressed air. In the present system, the heat is taken away from the quenching bath by the actual removal of the hot oil itself.

The usual methods are to pump the hot oil from the tank and then through coils which are cooled by suitable means; or by maintaining large supply tanks in which the oil will have sufficient time to cool before being returned to the quenching tank. In the former procedure the coils containing the hot oil may be cooled by refrigerating—such as the ammonia process, etc.—or by placing the coils in a water tank, or by cooling the coils with a continual stream or spray of water. Where the size of plant will permit the installation of a refrigerating system, such a method is by far the most satisfactory; the heat may be removed very quickly, and the temperature of the oil controlled at any desired temperature by the regulation of its flow through the cooling coils.

As an example of the water-bath method, one steel company pumps the oil from the quenching tank—holding some 12,000 gals.—through 3-in. pipes and thence through coils placed in a large water tank used for the mill supply. The cold oil then returns to the quenching tank by gravity.

For smaller plants the coils may be most conveniently cooled by the use of tiny streams of water trickling over the coils. On the whole, this is probably the most satisfactory system of all for small plants. In one case (in which the question of the cost of water was important) this method was found to be both cheaper and to give a higher cooling efficiency than could be obtained by setting the coils



in a small water tank. In the latter case the heat is removed by transference from one part of the water to that further removed from the coils, so that unless a very good flow is maintained, the cooling will be comparatively slow. Further, the water removed from the tank is, on the whole, but lukewarm, and therefore but imperfectly accomplishes its mission. On the other hand, in the drip system a small amount of cold water is always in contact with the coil, giving a maximum cooling efficiency with a minimum expense.

A recent heat treatment installation<sup>1</sup> attacks the problem of keeping the quenching medium at a uniform and low temperature by the maintenance of a large and separate supply of oil. The hardening is done in special quenching tank cars, as shown in Fig. 55, and which are wheeled to any furnace desired. Just before quenching commences the valve in pipe *K* is turned on and a 2-in. stream of cold oil is kept flowing into the tank. The hot oil passes out through the overflow pipe *L*, through the hole in the floor and into a pipe that conducts it into an underground tank. This underground pipe is made very large, so that there will be no danger of its clogging, which would necessitate tearing up the floor. Each furnace throughout the 400-ft. length of the shop is provided with a similar inlet pipe and floor hole connection to the pipe which carries away the overflow. From the underground tank the oil is pumped to upright tanks close to the outside of the building; from these tanks the oil flows by gravity to the tank cars.

**Use of Compressed Air.**—The advisability of using compressed air in the quenching tank is a much debated point. If applied intelligently, however, it undoubtedly renders great assistance in the hardening and cooling operations. In systems in which the oil is kept in constant and fairly rapid circulation, it is neither required nor advised.<sup>2</sup> But if the oil is cooled by the circulation of water in pipes, the use of compressed air is often mandatory in order to obtain the maximum, as well as uniform, cooling efficiency of both oil and water. In any case, the air must not be allowed to come in contact with the hot steel, as soft spots would result; neither should it be used in too great quantities nor pressure, especially with the heavier and low-grade oils, as it may cause the precipitation of

<sup>1</sup> "A Modern Heat-Treatment Plant," *Machinery*, Sept., 1914.

<sup>2</sup> The cold oil forced into the quenching tank may be distributed under pressure to different parts of the tank, thus providing excellent circulation, and accomplishing the same results as compressed air.

certain constituents of the oil, or cause the formation of a scum or foam on the surface of the oil. When the air sets up a fairly efficient

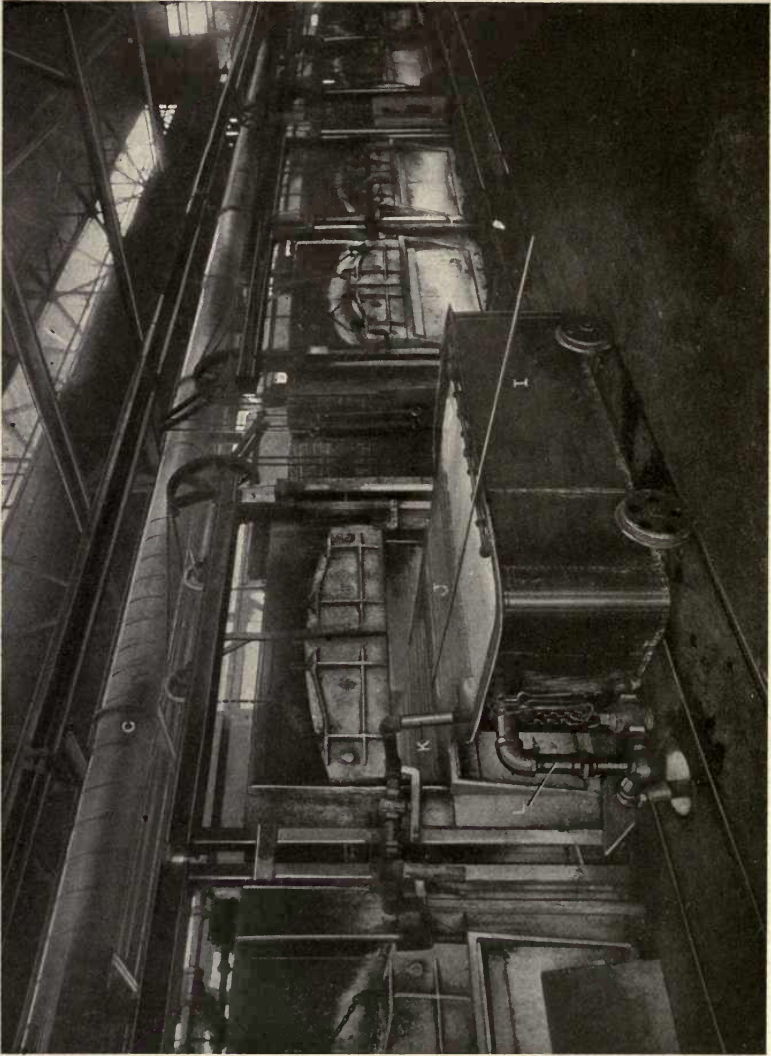


FIG. 55.—Oil Quenching Tank Ready for Receiving Automobile Drive Shafts from the Furnace.  
(" Machinery.")

circulation of the oil (or water, if water is the quenching bath), it has accomplished its mission. Compressed air should rarely be used with animal or vegetable oils on account of oxidation.



**Size of Quenching Tank.**—The volume of the quenching medium to be used, and hence the size of the tank, depends principally upon the size and number of the pieces to be hardened, and also upon the method used for cooling the quenching bath. The tank should always be of sufficient size to take with ease the maximum size stock to be treated, besides a generous allowance on all sides for a sufficient body of oil or water, for rapidity in handling the material, and for circulation. Further, the size of the tank should be proportioned to the degree to which the solution can be kept cooled when the hardening department is operating at maximum capacity; the more efficient the cooling system, the smaller the size of tank necessary. On the whole, it is decidedly preferable to have the tank too large than too small.

#### CRACKING AND WARPING

**Influence of Non-uniformity of Section on Cracking.**—One of the main causes of steel breaking in hardening is from the unequal contraction and expansion in different parts of the steel. If it were possible to get every particle of the steel cold at the same moment there would be an end to danger of this sort. But as this is a physical impossibility, we must approach such a condition as near as we can. This danger of cracking is particularly emphasized in forgings or tools of unequal thickness. If the thinner part should be first immersed in the quenching bath (e.g., water), it would become cool much sooner than the heavier sections; that is, the thin part would be cold or "fixed" while the thicker part of the article was still contracting from loss of heat. Hence the thin part in its then hard and brittle state cannot "give" and will consequently break; or, if it does not break at the time of hardening, the steel is held in such a state of stress that it is ready to break when applied to the work, or even when being tempered. These influences are the more marked with the greater the rapidity of cooling and hardening effect of the bath, as well as with the increase in carbon content and alloys.

**Influence of Bulk of Section on Cracking.**—Further, the danger of cracking is dependent upon the bulk of the article, even though it be of uniform section. Its effect is repeatedly illustrated by large forgings such as locomotive axles, crank-pins, etc., of rather high carbons quenched in water. This point is illustrated by the case of a locomotive crank-pin which had been hardened in water and then toughened. A thorough examination of the forging before shipment to the railroad company revealed no external evidences



of any crack; but when it had been in service but a very short time it fractured badly. Examination then showed that it had evidently been in a state of stress within its center, with the development of an embryo crack; the dynamic stresses to which it had been subjected in service were sufficient to raise the tension beyond what the steel would stand, with the resultant internal fracture and its progressive development into complete rupture.

**Expansion and Contraction.**—In view of recent research work this phenomenon of cracking may be explained in a theoretical manner along the following lines. We know that when a piece of steel is heated through the critical range the formation of austenite takes place with a *decrease* in volume; and a somewhat corresponding and opposite *increase* in volume occurs when it is *cooled* through the same critical range. Now if a large forging of considerable diameter is quenched rapidly, the outer sections will be held in the hardened condition, and therefore rigid and stressed. Meanwhile the interior of the steel, being cooled much less rapidly, will in all probability actually pass from the austenitic-martensitic condition into that of pearlite, accompanied by the increase of volume noted above. If the outer portion or surface of the steel is unable to withstand this expansive force, rupture must necessarily occur. Illustrative of this, the author has seen heavy locomotive axle forgings, after removal from the oil-hardening bath, actually break open with a tremendous report. However, if the forging has not been hardened too drastically, and is removed from the quenching bath before entirely cold, an immediate reheating or toughening process will generally relieve these stresses before any actual damage takes place.

**Hollow Boring.**—In order to avoid such dangers, there appears to be a decided tendency toward requiring the drilling of axles, shafts and heavy forgings of large diameters to provide for heat treatment and to remove defective material. It is undoubtedly the fact that heat treatment will not attain its full effects in the core of a large section. With a solid axle, the heat, upon quenching, is removed by a flowing from the center to the outside and thence to the hardening bath; the amount of heat is so great, however, that at the best the core will be but semi-hardened, and in most cases will but be grain-refined, or annealed. This point was well illustrated by one company in its experiments: it split open a large, heat-treated driving axle; the fracture showed that the heat treatment had penetrated the ends to a depth of about 6 or 8 ins., and on the

sides to a depth of about one-half the radius; the fracture of the core was similar to that of annealed steel. Again, the loss of ductility and failure of the heat-treatment process thoroughly to penetrate the core of semi-hardened steel are shown by the following results obtained from a 12-in. axle, heat treated, and taken at regular intervals from the center to the outside:

	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation, per Cent in 2 Ins.	Reduction of Area, per Cent.
1. (Center)	95,000	60,000	7.5	9.6
2.	99,750	60,000	15.0	35.3
3.	104,500	65,000	17.5	35.7
4.	104,500	65,500	19.0	40.3
5. (Outside)	106,500	70,000	21.5	47.7

Treatment: Quenched in water from 1580° F.; toughened at 1100° F.

Analysis: Carbon, 0.35; manganese, 0.56; phosphorus, 0.020; sulphur, 0.024; nickel, 1.19; chrome, 0.31.

By means of drilling a hole through the axle, the quenching solution is able to remove the heat from both the inner and outer part of the axle at the same time. Hollow-bored axles should be quenched vertically whenever possible, and a constant flow of the oil or water through the bore be supplied.

The American Railway Master Mechanics' Association in its proposed specifications for alloy steel locomotive forgings (June, 1914) calls for "drilling forgings over 7 ins. in diameter, unless otherwise specified by the purchaser. The committee has found a great tendency among users of quenched and tempered steel to require drilling of parts over 7 ins., and this practice is advocated by steel-makers. In the case of axles and crank-pins particularly, drilling takes away practically nothing from the strength of the part; it removes the material from the center where defective material is most likely to exist and where it is least subject to the beneficial effects of heat treatment, and it allows the forging to adapt itself to expansion and contraction due to heating and cooling."

**Warping.**—Warping is but another manifestation of the effect of unequal contraction and expansion, originating mainly in incorrect heating or neglect in the manner of quenching, rather than in the more drastic effect of the bath itself. Non-uniform heating must inevitably result in warping, for if some parts are hotter than others when the steel is quenched, it is evident that the rate of cooling over the entire length of the piece cannot be the same. The general



tendency will be for bars to buckle or twist, due to unequal contraction during hardening. Take, for example, a bar which has been placed upon the relatively cold floor of a heating furnace in which the main heat application comes from above. Under these conditions the tendency will be for the bar to become more heated along the upper surface than in that in contact with the cold floor. If the bar should now be quenched, the under part—being lower in temperature—would contract first (provided it were heated and quenched from a temperature over the critical range) and thus become bowed. But if the temperature in the cooler part of the bar were under the critical range, the tendency would be to bend in the opposite direction. Other variations in heating might give a double bend; certain localized heating might even cause twisting or torsional strains.

**Manner of Quenching.**—Uniformity of quenching is requisite to good hardening work. As a general rule, objects should be quenched vertically in the direction of their greatest length. Like all rules, there are certain exceptions which must be made to this general statement—such as in the case of half-rounds and articles of a corresponding design, as well as in such cases where economic handling requires other methods, as with shafts, small axles, plates, etc. But where no special facilities have been designed for uniform quenching, the above rule will be found worthy of adoption for symmetrical sections, and especially with unskilled workmen.

The reasons for this may be best explained by taking small automobile drive-shafts as an example. In pulling the piece out of the furnace with the tongs, the tendency is to grasp it nearer the end than at the middle; consequently, in the general haste to get the steel into the quenching bath as soon as possible, the average workman is very apt to drop or plunge it into the oil or water at an angle—that is, one end of the piece strikes the quenching solution before the remainder of the steel. Hence, initial hardening strains are set up which usually result in a bent shaft when it is removed from the tank. It is very difficult, in the space of a second or two, to get hold of the bar exactly at the middle and also to lower it into the water or oil so that both ends are immersed at the same identical moment—which this method of quenching demands. Now if the workman was to aim at immersing the piece end foremost, as in Fig. 56, grasping it near the end (as usual) with his tongs, the weight of the shaft would automatically tend to bring the shaft to the normal, and the quenching would be more nearly uniform. Axles and



forgings of a similar nature should be quenched vertically whenever possible, as less strains are set up in the axle by this mode of quenching. Extensive investigations by one locomotive builder would tend to show that axles quenched horizontally (as is customary) develop a series of stresses which, when plotted, appear as an oval around the axis of the axle instead of as a circle.



FIG. 56.—Proper Method of Quenching Small Round Bars.

Hollow forgings, such as guns, hollow tools, etc., should always be quenched vertically, so that the quenching medium may have a free flow through the bore, and also to prevent the pocketing of any steam or vapor which may be formed by the contact of the hot steel and the solution.

**Round Sections.**—The hardening of round sections without cracking or bending, and without undue labor cost, presents a problem

which has attracted much study. The danger of fracture, especially of internal origin—whether actual or potential—is always greatest in the circular section. This is largely due to the fact that all the stresses and their subsequent strains are grouped symmetrically and converge upon the central axis. Both the square bar with its corners, and the plate or sheet with its larger surface exposure, can more easily yield to the internal stresses and afford relief—either in cooling during hardening or in the reheating for tempering or toughening—than can the circular section. Further, there is greater danger of bending and twisting due to non-uniform cooling in the long, round bar than in almost any other common section. As has been noted, short lengths of rounds of small diameter should always be quenched vertically. But when it comes to the handling of large numbers of larger bars, either of greater length or diameter, this method is obviously at a disadvantage. Yet if the bars are simply dropped into the bath by hand, even if every effort is made to have the axis of the bar parallel to the surface of the quenching medium, general unsatisfactory results are obtained, due to non-uniform cooling.

One satisfactory method for quenching such bars is shown in Fig. 55, in which automobile shafts are handled. The bars, after careful heating, are pulled out with long rods which have a hooked end, across the inclined steel fore-hearth *J*, whence they drop on to a jointed rack in the oil tank and are quenched. By starting the bars with their axes parallel to the surface of the oil, they must necessarily be held in the same relative position as they pass down the rack into the oil. The rolling also effects a more uniform cooling of the shaft in relation to its central axis. Fig. 57 shows how the traveling crane lifts one side of this jointed rack to raise the shafts out of the oil and dumps them on to the truck at the side.

✓ An improvement on this method to give further uniformity in cooling, and which has been used on *finished* shafts with almost the entire elimination of bending, is illustrated in principle in Fig. 58. The apparatus consists of a number of inclined planes or racks (similar to that shown in Fig. 57), made from small bars or old rails which are held in position by suitable cross-pieces. The hot shaft is started down the first plane and passes into the oil or water; thence it drops to the next, and so on until it reaches the bottom, and is removed by suitable methods. Notice that the change from one plane to the next causes a reversal in the direction of rolling, so that any stresses set up by one plane are practically counteracted by the next plane, giving a maximum uniformity in cooling. The

angle of incline has a great deal to do with the practical working out of the procedure, and should be varied according to the diameter of

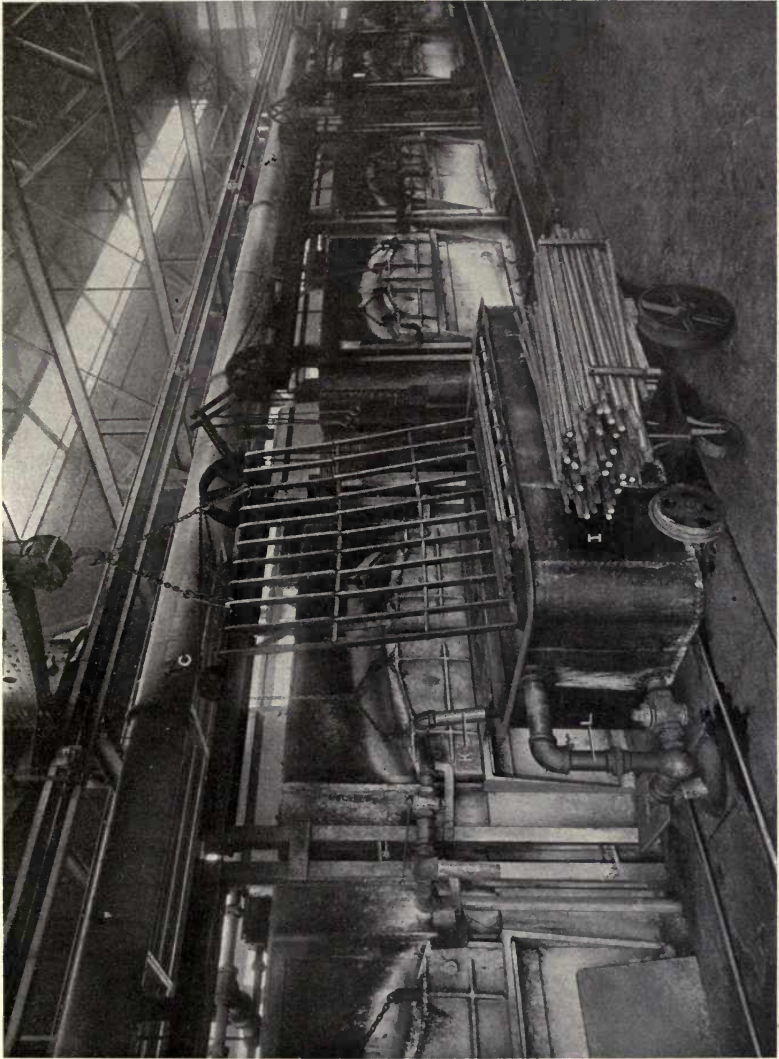


FIG. 57.—Dumping the Drive Shafts from an Oil Quenching Tank into Truck. ("Machinery.")

the bar, its chemical composition, and the nature of the quenching medium. The rate of travel down the incline should not be too rapid, but should nevertheless be sufficient to allow the reversing



action of the several planes to take its effect before the steel is too cold. The angle of the planes may be increased as greater depth in the solution is reached. The bar should be cold when it reaches the bottom of the tank. The angle of the first incline is the most important, and should be determined by experiment; it will generally be in the vicinity of  $10^{\circ}$  or  $15^{\circ}$ . In one plant in which this method was used the number of shafts requiring straightening was reduced from a very high percentage to less than 1 per cent. of the total number treated.

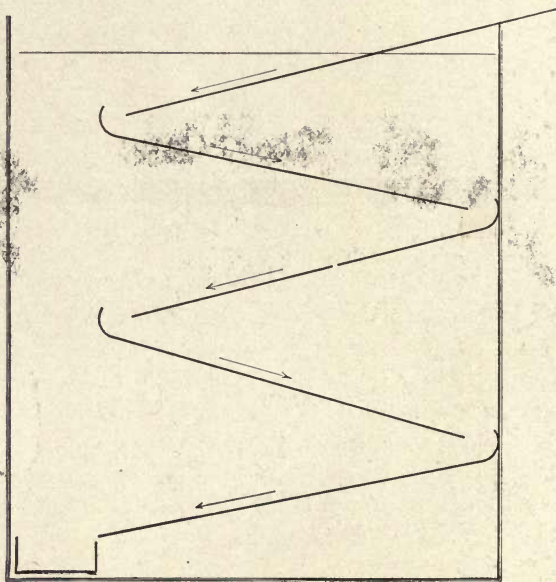


FIG. 58.—Rough Sketch of Inclined Racks for Quenching Rounds.

**Double Quenching.**—The effect of a double quench is, as a general rule, to raise the elastic limit and tensile strength without diminishing the ductility. This is for the most part due to the higher degree of refinement which this double quenching makes possible, thus putting the steel in the best possible condition. If the steel is in good condition (i.e., refinement) before the first quenching, the influence of the second quenching will be the less in proportion. It is often customary first to quench from a temperature  $100^{\circ}$  or  $200^{\circ}$  F. over the critical range, and then, for the second quenching, to heat just enough over the critical range to obtain the degree of hardness desired.

For high-carbon steels the double quenching is not to be recommended except under unusual conditions—such, for example, when the steel has been greatly overheated in some previous operation. The hardening of high-carbon steels is at best a difficult operation, and the less heating to which such steel is subjected the better.

**Manganese on Hardening.**—As we have previously mentioned, the presence of manganese causes a greater hardening effect, due to its obstructing the austenite transition. This increase in hardness—in ordinary carbon steels with less than 1.75 per cent. manganese—is commonly thought to be associated with an increase in brittleness,<sup>1</sup> and with the danger of cracking during or immediately subsequent to quenching. Forethought must therefore be used in obtaining the proper combination of manganese, carbon, and rate of cooling to avoid the latter difficulty. The general limits of safety for practical work may be broadly (but not invariably) set somewhat as follows: water quenching is always dangerous when the manganese content runs up around 1.50 per cent., even in low-carbon steels; with approximately 1.00 per cent. manganese water quenching may be used—although not advised—with mild forging steels; with the progressive increase in carbon the manganese content should be rapidly lowered, so that in tool steels for water hardening the manganese is under 0.40 per cent., and with very high-carbon tools is not over 0.25 per cent. Dependent upon the size and general shape (design) of the piece, as well as the condition (refinement) of the steel, oil quenching is generally safe up to 1.75 per cent. manganese with 0.60 per cent. carbon—in fact, one well-known oil-hardening tool steel analyzes about 0.90 per cent. carbon with 1.60 per cent. manganese. The subject of high manganese steels will be considered under a separate chapter.

<sup>1</sup> Refer to Chapter XV for a further discussion of this point.

## CHAPTER V

### TEMPERING AND TOUGHENING

#### TEMPERING

**Tempering.**—When a piece of carbon tool steel is heated to a red heat and quenched in water (i.e., hardened), the steel becomes hard, brittle, and is held in such a state of stress that its use—except in a few particular cases—would be highly inadvisable. This hardening operation has arrested the austenitic transition at the martensitic stage, and prevented it from advancing further, as into troostite, etc. Under these circumstances, the application of heat will now accomplish two results: (1) it will relieve the hardening strains, and (2) permit the transition to proceed. By properly adjusting the temperature of this reheating process, any desired stage in the martensite-troostite transition may be obtained. And by permitting just the right amount of the hard, brittle martensite to go over into the softer and tougher troostite, any desired combination of physical properties within the capacity of that particular steel may be realized. This process of “letting down” or softening is called tempering.

**Troostite.**—If the steel has been fully hardened so that it consists entirely of martensite, troostite will begin to form at somewhere in the vicinity of 400° F., or possibly lower. As the tempering temperature is progressively raised, the troostite increases in amount until at about 750° F. it begins to change into sorbite. Thus steel in the tempered condition is usually characterized by the presence of more or less troostite, dependent upon the degree of hardening and upon the tempering. Just as martensite may be said to represent the condition of hardened steel, or pearlite that of annealed steel, so troostite is indicative of a tempered steel—whether it be obtained by water quenching and reheating, or by quenching in some less drastic medium such as oil but with no reheating. The question of whether troostite represents a complete step in the transformation is not definitely known, and as far as practical heat-treatment work



is concerned is but a question of scientific value; the value of troostite in its influence upon the hardness and allied properties of tempered steel is, however, definitely recognized.

**Hardening Strains.**—It should be always remembered that tempering not only softens the steel through the influence of troostite, but also relieves the strains set up in hardening. This last factor should not be lost sight of, for although the proper degree of hardness is requisite for specific work, no tool will eventually prove of much value if it retains the state of strain occasioned by rapid cooling. This statement applies not only to water quenching, but also to oil quenching (or oil tempering). Even the influence of boiling water is often sufficient to relieve more or less of these strains, if it is not desired to further soften the steel by higher reheating. Naturally, however, the higher the softening temperature the better will be the condition of the steel in this regard.

**Temper Colors.**—Nature has provided a useful and more or less empirical indication of the degree to which tempering has affected the steel through the formation of a surface film of oxide colors (oxide of iron). If a piece of hardened steel is brightened with emery paper or other suitable means, and is then slowly heated with exposure to the air, the brightened surface will take on characteristic "temper colors." These commence with a very faint yellow and progressively change with increase of temperature through varying degrees of yellow, brown, purple and blue. That these colors bear a definite relation to, and are closely indicative of, a known temperature, under certain conditions, is now a generally accepted fact. Although a difference in distinguishing the various shades of color is bound to occur on account of the "personal equation," the following table is fairly representative:

Temperature, Degrees Fahr.	Color.	Temperature, Degrees Fahr.	Color.
420	Very faint yellow	510	Brown
430	Yellowish-white or light straw	520	Brown purple (peacock)
440	Light yellow	530	Light purple
450	Pale yellow straw	540	Purple
460	Straw	550	Dark purple
470	Dark Yellow	560	Light blue
480	Deep straw	570	Blue
490	Yellow brown	600	Dark blue
500	Brown yellow	625	Blue tinged with green

**Limitation of Color Method.**—The previous statement regarding the relation of tempering colors to temperature is true in its entirety only under certain definite conditions of heating, and which are largely dependent upon the time element. So long as the heat of the steel is being progressively raised—that is, so long as the temperature of the fire, furnace or tempering plate is greater than the temperature of the steel—the temper colors indicate the temperature of that part of the steel most affected—the surface. But when the steel is being kept at a definite tempering temperature for any length of time, the colors do not represent the actual temperature. This point is readily illustrated by heating a small piece of hardened steel at a constant temperature for a considerable period of time. Thus, in one instance, a straw color was produced in about a minute, but changed to a brown in about ten minutes, and to a purple in about forty minutes; and yet the temperature of the steel was never higher than  $460^{\circ}$  F., representative of the straw color. In other words, the time element has developed a new set of conditions which may greatly affect the depth of oxidation or color.

On the other hand, it is a debatable point as to whether or not these temper colors represent the actual condition (not the temperature) of the steel itself. Some tool makers maintain that the efficiency of the tool—both in hardness and in other properties—is the same whether the color has been obtained by a short heating at a high temperature, or a longer heating at a lower temperature. That is, the ultimate results are indicated by the temper color, independent of the method of obtaining it. Others aver that such is not the case.

**Tempering for Depth.**—It is obvious that the temper color is at the best but a surface indication. For some tools or articles which require a specific superficial hardness only, and in which the condition of the center of the tool is of little consequence, it probably does not matter a great deal in the ultimate results whether the temper color—a straw color for example—has been obtained by a few minutes' heating at  $460^{\circ}$  F., or by heating for a longer period at say  $360^{\circ}$  F. Contrariwise, if the tool or part is to be subjected to stresses of such nature as demand the best that the steel is capable of, the greatest degree of uniformity and release of hardening strains is requisite. Such may only be obtained by a thorough heating at a specified temperature, and which may be entirely independent of the color indication. In such cases, to use the above temperatures, the thorough heating at  $360^{\circ}$ —it more uniformly affecting the whole mass of the steel—might prove immeasurably better than the



incidental surface heating to  $460^{\circ}$ . And as will be mentioned later, a continued heating at  $460^{\circ}$  would again be an improvement over either color method.

**Quenching after Tempering.**—The method of tempering by color indication inherently requires immersion when the specified color is reached to prevent any further rise in temperature, or in the blacksmith's phrase, to "set the grain." Although it is possible so carefully to heat the steel that the maximum effect is just to develop the color desired—and no further, such methods take so much time and patience that they are rarely carried out in practice. The necessity of such immersion or quenching, even in the hands of an experienced hardener, is the source of many troubles. Not only does the quenching probably induce further strains into the steel, but it is also entirely inconsistent with uniformity of results. If the object is of considerable size, or varies greatly in dimension of adjoining sections to be similarly tempered, or is of intricate design, the difficulty in obtaining the same temper throughout even on the surface (to say nothing of the interior of the steel), will be greatly magnified. If the proper color is reached on one part before another, there will be a corresponding difference in hardness. And thus the difficulties multiply *ad infinitum*.

**Use of Liquid Baths.**—Later methods involving the use of liquid baths for heating overcome the difficulties in color tempering, eliminate—as a general rule—the necessity for quenching, and further give complete uniformity of heating throughout the whole mass of the steel and the maximum elimination of hardening strains as can be obtained at the temperature used. By maintaining the bath at the proper temperature there can be no overheating, the heat must penetrate all parts of the steel alike, and the "personal equation" is as nearly eliminated as is possible. This method has the further advantage of cutting down labor costs and increasing the output, since a number of pieces may be heated at the same time, and while one lot is being tempered another bath may be charged or discharged.

**Comparison of Physical Properties Obtained.**—An excellent example of the efficiency of bath tempering is illustrated in automobile gears. On account of the relatively thin section of the teeth as compared with the mass of the gear, exact tempering by the ordinary temper-color practice is rather difficult. The teeth, which should be the hardest, take the temper first, and are therefore the softest part of the gear as a whole. If the gears were to be tem-



pered by revolving on a hot bar much better results would be obtained than by ordinary tempering, but the time and cost elements would prove excessive where hundreds of pieces were to be handled. By the use of a suitable liquid tempering bath thorough uniformity could be obtained throughout. Where by the color method, the core of the gear would have the tendency to be too hard, the teeth perhaps too brittle or soft in places, and only the surface of the gear as a whole affected by the temper-color representing say 475° F., by the more modern method the whole mass of the gear would have the physical properties as characterized the drawing temperature of the 475° F.

**Exact Temperatures.**—Too much attention cannot be given to the necessity of obtaining exact temperatures in the tempering operation. For the average run of carbon tools the tempering range is very narrow, probably within a hundred degrees for the great majority. The tempering action takes place extremely rapidly and often a difference of 15° or 20° may cause much trouble. Trying to temper tools over an open fire may be all right in isolated cases, but it spells failure if made a general practice.

**Tempering Methods.**—The procedure to be employed in tempering must necessarily depend upon the nature of the tool or part. Methods must be developed to satisfy the individual requirements and are too numerous to discuss here. Briefly, however, the more common practices may be covered by the tempering plate, the sand bath, and such liquid baths as oil, lead and alloys, and molten salts.

**Tempering Plate.**—The tempering plate generally consists of an iron casting planed smooth on top, and heated from beneath by suitable means, such as gas, oil, or even a coal or coke fire. The steel articles are placed on the plate and moved about until they have attained the proper temper color and then quenched. Fig. 59 shows a characteristic equipment for heating, hardening and tempering dies; *Q* represents the discharge end of the heating furnace, *R* the quenching tank, and *T* the tempering plate, the latter being heated by oil burners from beneath.

**Sand Bath.**—In order to effect more uniform tempering of small tools, a pan of clean, well-dried sand may be placed on a suitable hot-plate, or in a furnace. The sand is held at the desired temperature, which may be determined by the insertion of a thermometer or pyrometer couple, and may be protected by covering with a suitable hood. The oxide colors on the steel may also be

used as a measure of the tempering, as there is of course free access of air between the particles of the sand.

**Oil Baths.**—For much of the ordinary tempering work an oil bath will probably prove as satisfactory as any method for temperatures up to about  $500^{\circ}$  F. or even higher. The chief requisites are a tank holding an ample supply of oil, a suitable furnace or method of heating by which accurate and constant temperatures may be obtained, and a mercury thermometer for determining the temperature of the oil. Mineral oil with a flash-point of some  $600^{\circ}$  F. is

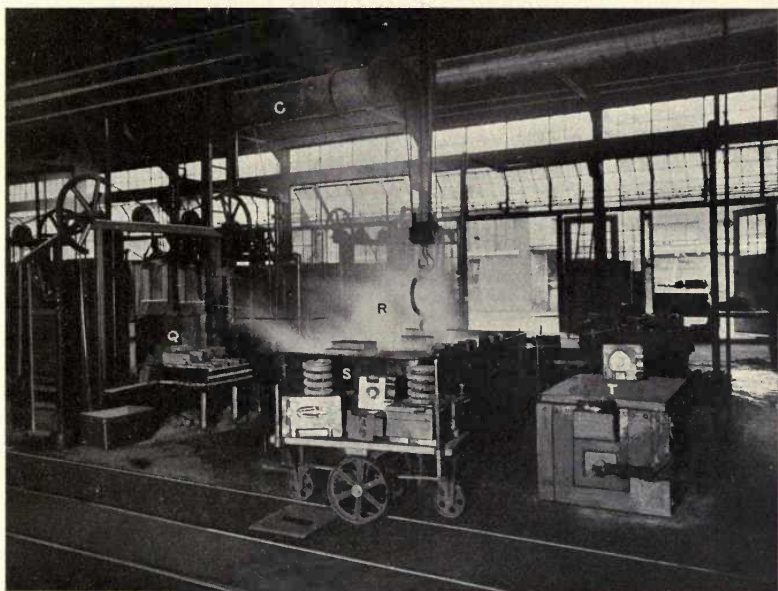


FIG. 59.—Quenching and Tempering Dies. ("Machinery.")

generally used for the bath; certain of the animal and vegetable oils are also occasionally used.

**Handling the Material.**—Oil baths, and similarly the salt baths, are provided with a wire basket in which the pieces to be tempered are placed and which is then lowered into the oil. By this method a number of pieces may be tempered at once, besides preventing the steel from coming in contact with the sides or bottom of the tank, which is apt to be hotter than the oil. It is advisable, whenever possible, to allow the hardened steel to



come up gradually to the desired temperature, and not to immerse in the oil when the latter is already at the highest heat. Rather put the steel in the oil when the latter is about 200° to 300° F. and let the two heat up together. The reason for this is that the pre-heating—if it may be thus termed—allows the heat to penetrate more gradually, softening the outer portion of the steel in such a way that the inner and stressed part may be more gradually relieved and thus avoiding the danger of fracture. Sudden heating has the tendency to set up new stresses which must in turn be overcome. The length of time allowed for the tempering to take place will depend upon the size and nature of the piece under treatment; fifteen minutes or so after the maximum temperature has been reached will generally be sufficient for the average run of small tools, gears, etc., while larger parts require more time in proportion. If large and small parts are tempered at the same time it will do no harm to the small pieces if they are not removed until the larger pieces are ready, although on general principles long-continued heating is never desirable after the steel has responded to the desired heating. When the full effect of the tempering has been attained, the pieces may then be removed from the oil and allowed to cool off in the air, for if the steel has been thoroughly heated at the maximum temperature of the tempering operation, no further change will take place in the ordinary steels; each phase of the transition is represented by a definite temperature for each steel, so that no further step in the transition will occur unless the temperature is raised—with the possible theoretic exception of very long-continued heating. For some large work, such as die blocks, large cutters, etc., the steel is allowed to cool off in the oil in order to procure the greatest elimination of strains.

**Salt Baths.**—If higher drawing temperatures than those possible with oil are desired, a bath of salts may be used. A combination of two parts of potassium nitrate and three parts of sodium nitrate melts at about 450° F. and may be used up to about 1000° F. Methods of heating and using are similar to those with oil baths, and described under Hardening Baths. The use of nitrate salts instead of the chloride salts is necessary on account of the lower temperature desired.

**Lead Baths; Alloys.**—Lead, having a melting-point of about 610° to 630° F., may also be used for tempering where temperatures higher than its melting-point are required. The disadvantages are similar to those noted under its use for heating for hardening. The



melting-point may be lowered by alloying the lead with tin, and temperatures suitable for ordinary tempering may be obtained approximately as follows:<sup>1</sup>

Lead Parts.	Tin Parts.	Approx. Melting Temp. ° F.	Lead Parts.	Tin Parts.	Approx. Melting Temp. ° F.
14	8	420	28	8	490
15	8	430	38	8	510
16	8	440	60	8	530
17	8	450	96	8	550
18.5	8	460	200	8	560
20	8	470	Melted lead	.....	610 to 630
24	8	480			

The use of these various alloys of predetermined melting-points for tempering is similar to that previously explained when selecting a combination of salts with certain melting-point in the hardening operation.

#### TOUGHENING

**Sorbite.**—As the reheating or drawing temperature is increased still further beyond the tempering range we find that another stage in the austenitic transition commences—the change of troostite into sorbite. Like the change from martensite to troostite, the formation of sorbite does not take place spontaneously throughout the whole steel, but increases gradually and progressively. Most writers believe that sorbite is essentially an uncoagulated conglomerate of irresoluble pearlite with ferrite in hypo-eutectoid (less than about 0.85 per cent. carbon), and cementite in hyper-eutectoid steels respectively, but that it often contains some incompletely transformed matter. Its components at all times tend to coagulate into pearlite. On higher heating, sorbite changes into sorbitic pearlite, then slowly into granular pearlite, and probably indirectly into lamellar pearlite. Sorbite differs from troostite in that it is softer for a given carbon content, and in usually being associated with pearlite instead of martensite, and from pearlite in being irresoluble into separate particles of ferrite and cementite.

**Importance of Sorbite.**—The main importance of sorbite is due to its physical properties. Although slightly less ductile than pearlitic steel for a given carbon content, its tenacity and elastic limit are so high that a higher combination of these three properties can be

<sup>1</sup> Table by O. M. Becker, using melting-point of lead as 610° F.

had in sorbitic than in pearlitic steels. Steels which are so treated as to contain sorbite are often called "toughened" steel.

**Toughening Range.**—The transition of troostite—the chief characteristic of tempered steel, into sorbite—characteristic of toughened steel, is gradual, and progresses with the increase and duration of the reheating. At some point, depending upon the composition of the steel and the degree to which the steel has been affected by the hardening process, sorbite is formed. If we accept sorbite as the characteristic constituent of toughened steel (and which it undoubtedly is), we may then consider as the lower limit of the toughening range that temperature which will produce sorbite. In fully hardened steel of the medium forging and higher carbon analyses, characteristic sorbite begins to form at about 750° F. At about 1250° to 1300° F. the sorbite coagulates into pearlite, which is distinctive of annealed steel. With these facts in view we may then consider, in a general way, that the toughening range lays approximately between 750° and 1250° F. It must be remembered, nevertheless, that these temperatures are in no sense definite, but are arbitrarily taken as representative of a class of heat-treatment work: differences in chemical composition, the degree of hardening, the size of work, etc., all play their part.

**Influence of Toughening.**—When a piece of hardened steel is reheated for toughening, each specific temperature has a certain definite influence upon the steel. The results of this toughening process are interpreted by the ability of the steel to do certain work, to withstand the application of stated loads, or as measured by standard methods of testing. On account of the almost universal use of the last named for purposes of comparison, we will deal briefly with (1) the static strength, as measured by the tensile strength and elastic limit, (2) the ductility, as measured by the percentage elongation and reduction of area, and (3) the dynamic strength, as measured by the alternating impact test.

**Effect of Increased Temperature.**—Each increase in the toughening temperature lowers the tensile strength and elastic limit, but with a corresponding increase in the ductility and dynamic endurance. With the majority of ordinary carbon, nickel, chrome and vanadium steels the ratio of the elastic limit to the tensile strength remains very nearly constant throughout the sorbitic range (which we assumed to be approximately from 750° to about 1250° F.). Beyond these temperatures, and coincident with the formation of pearlite, the values for the elastic limit and tensile strength—of each par-

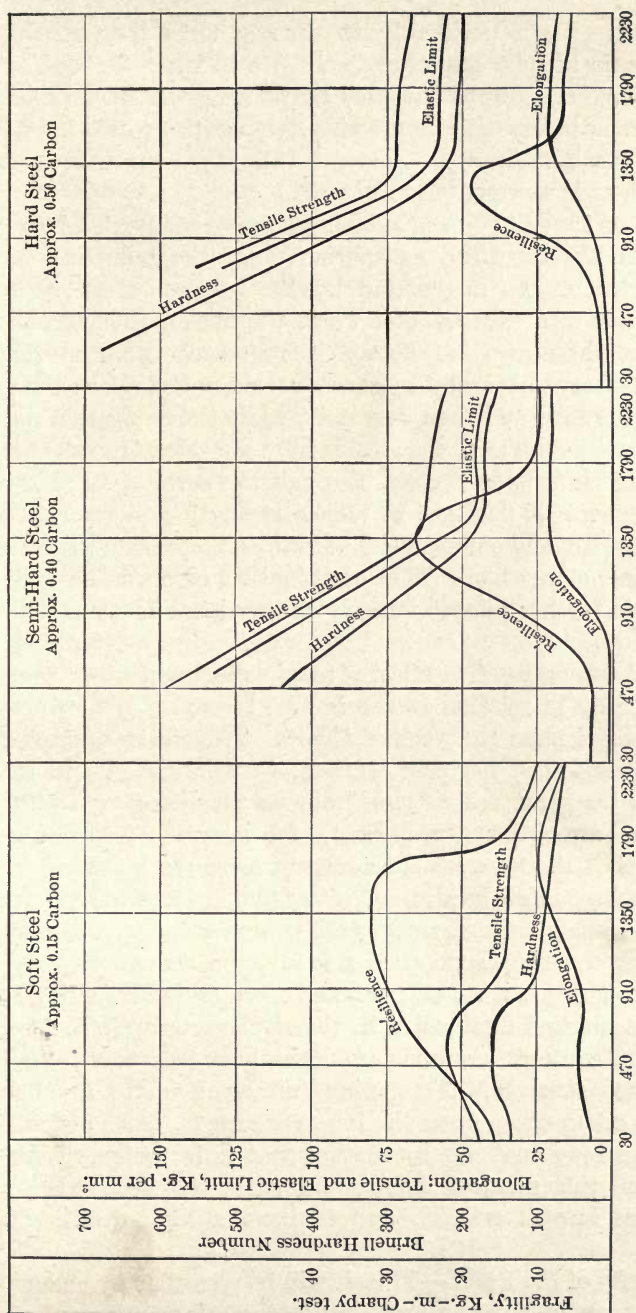


Fig. 60—Variation of the Mechanical Properties with the Drawing Temperature.



ticular steel—begin noticeably to diverge until they reach their smallest ratio in fully annealed steel. Up to near the end of the sorbitic range the graphs obtained by plotting the elastic limit and tensile strength against the drawing temperatures are, for general purposes, straight lines, but beyond this range curve towards the horizontal, as is represented in Fig. 60.

**Effect on Ductility.**—These changes are accompanied by reverse changes in the ductility, as measured by the reduction of area and elongation. As interpreted by the research work of others, and from his own experimental work, the author is inclined to the belief that these two factors differ from each other in that the reduction of area generally reaches a maximum at about the end of the sorbitic range and then decreases, while the elongation does not attain its maximum until the steel is fully annealed or in the pearlitic condition. Be this as it may, through the sorbitic stage at least, each increment of decrease in tensile strength and elastic limit is associated with, and counterbalanced by, an increase in the reduction of area and elongation. This combination of static strength and ductility is further almost directly proportional to the toughening temperature.

**Impact Strength.**—The effect of toughening upon other properties and especially in relation to the impact strength, is shown in Fig. 60, rearranged from the work of Grard. The steels, approximating 0.15, 0.40 and 0.50 per cent. carbon, were hardened and then reheated to temperatures varying from no tempering up to 2200° F. The impact strength curves present some extremely interesting facts. We find that the greatest resistance to shock to be obtained from a toughening, after hardening, at a temperature about 100° F. below the upper critical range ( $A_{c3}$ ); annealing at a temperature superior to the  $A_{c3}$  range gives a lower impact strength. Further, as the temperature is raised more and more and overheating results, there is a marked diminution in the impact strength. Increase in the carbon content, assuming the same heat treatment, diminishes the impact strength. Tempering (reheating up to say 600° F.) has little or no effect upon the impact strength. As a general proposition we may sum up by stating that it is preferable, in order to obtain the greatest impact strength, to keep the carbon content as low as possible and to have a high drawing temperature.

**Capacity of the Steel.**—Thus it will be seen that by changing the drawing temperature the grouping of these factors may be varied

through a considerable range and limited only by what we may call, for want of a better phrase, the "capacity of the steel." This quantity is defined largely by the chemical composition, the method of manufacture, the size of the piece to be treated, and by other subordinate factors. With these qualifying conditions in mind, we may further define the capacity of the steel as the limiting ratio of strength to ductility. Each steel, as qualified above, has certain definite limits within which the physical properties may be varied. At one end of the see-saw, as in hardened steel, there is a maximum tensile strength with minimum ductility; and at the other extreme, as in fully annealed or sorbitic-pearlitic steel, there will be a minimum tensile strength with maximum ductility. Following out the simile of the see-saw, we may place tenacity on one end and ductility on the other; when one is up, the other must be down; both cannot be up nor both down at one and the same time; raise one and the other must fall. The heat-treatment man now stands on the middle of the board and by means of his reheating temperature can adjust the opposing factors to that position which he desires; but he cannot change the maximum and minimum of either, because they are fixed by the limitations previously mentioned at the beginning of the paragraph, and over these he has no control as far as the individual steel is concerned.

**Duplication of Results.**—Happily for the heat-treatment man, each grouping is distinctive of a definite toughening temperature, other conditions being the same. When he has once determined the relation existing between static strength, ductility, and temperature, for a given size piece of work made from a steel of specific analysis, he knows that he can approximately duplicate his results under like conditions at any time. Not that he can absolutely and ultra-scientifically obtain results within a few pounds elastic limit or hundredths of a per cent. elongation—for such are neither necessary nor expected—but that he can reasonably expect to get a commercially acceptable duplication. It is with this thought in mind that the subsequent chapters have been developed, giving under each steel many of the results and details which have been obtained in practice and experiment, and which should prove advantageous to the average heat-treatment man as a time-saver.

**Slow Cooling and Stresses and Strains.**—It is one of the incontrovertible facts of heat-treatment work that slow cooling predicates the release of internal stresses and strains. Not only is this true of the full-annealing process—as indicative of slow cooling from a



temperature above that of the critical range, but also of the toughening operation. In fact, the very nature of the usefulness of toughened steel depends upon the absence of a state of strain just as much as upon specific static or dynamic properties. Strange as it may seem, some of the failures in locomotive forgings may be traced back to the lack of slow cooling after toughening; and this trouble is coming to be recognized in many specifications by the requirement of cooling in the furnace after toughening. Just as the dangers in hardening increase with the rapidity of cooling, carbon content and size of section, so are they likewise magnified in cooling after toughening—although on a smaller scale. If these factors become noticeably important, cooling in air from the toughening temperature may set up such a new series of cooling strains that many of the real advantages of toughening may be invalidated.

**Use of Furnace Cooling.**—The greater part of hardened and toughened work, such as automobile and other small forgings, may not require furnace cooling, besides being economically impracticable. But even with these it is desirable that the pieces should be piled together after removal from the furnace so that the cooling will be retarded. For forgings of section greater than 3 or 4 ins., such as heavy machine parts, ordnance, etc., cooling in the furnace is always desirable. It may be said that such slow cooling never did any harm, and it may do a world of good in relieving strains.

**Effect of Furnace Cooling on Physical Properties.**—Contrary to the opinion held by some, the author does not believe that slow cooling in the furnace has any noticeable tendency to further “soften” the usual straight carbon or alloy steels to which the toughening process is generally applied. That is, for similar pieces of the same steel treated alike, equivalent *physical test* results would be obtained in the forging which had been furnace cooled as in the one which had been allowed to cool in the air—the tests being taken from the same relative position. In making this statement there is, however, one other necessary qualification: it is assumed that the whole mass of the steel has been *thoroughly* heated at the toughening temperature. Otherwise the effect of the toughening would not be so great in the air-cooled piece as in the slowly cooled piece, for the latter would have greater opportunity to be affected by the heat of the furnace during the furnace cooling. During the toughening range the effect of the heat upon the transition, except for very large pieces, practically ceases as soon as the source of heat is removed—as by air cooling.



**High vs. Low Toughening Temperatures.**—On the hypothesis that either of two specified analyses would prove equally satisfactory, under suitable treatment, for the same piece of work, but that on account of the difference in chemical composition one steel would require toughening at say 1200° F. and the other at say 800° or 900° F., the selection of the higher drawing-point steel should be made. Such conditions often arise in heat-treatment plants handling a variety of commercial work and it may be well to sum up briefly the reasons for the above conclusion.

The more stable the state of equilibrium which exists between the transition constituents the more lasting and effectual will be the treatment. Further, the smaller the amount of internal strains which may remain in the steel from the previous hardening operation the better. Both of these conditions are more nearly brought about by the higher drawing temperature.

As there is also a decided tendency for the dynamic strength to reach a maximum at about 1200° to 1300° F. it is probable that the higher drawing temperature steel will have a greater dynamic strength than the other steel, provided that there is not too much difference between the chemical compositions of the two steels.

From the furnace man's point of view the temperatures around 1200°, being of characteristic visible reds, are decidedly more easily recognizable than those temperatures around 800° to 1000°, since with these lower temperatures there is very little visible heat color. The higher drawing temperatures therefore aid in the efficiency of judging the heating operation and lead to greater uniformity of control and of results.

**Quenching Medium vs. Toughening Temperature.**—There is another phase of the high or low toughening temperature proposition which cannot be solved by any general rule, but only after due consideration of all the circumstances involved; this relates to the condition of affairs when there is no opportunity for the choice of steel, but depends more upon the selection of the quenching medium in relation to the toughening temperature. As we have noted, water quenching gives a harder steel than oil quenching. It naturally follows that, in order to obtain approximately the same physical results, the oil-quenched piece must be drawn at a lower temperature than the water-quenched piece. The arguments regarding water vs. oil quenching, and low vs. high drawing temperatures have been previously discussed. If the solution were to be developed entirely along these lines it is probable that in the majority of cases

the oil quenching (giving less hardening strains) and lower drawing temperature would be employed. In other words, the difficulties to be encountered with water quenching—the hardening operation being the more drastic of the two—would more than outweigh the the disadvantages of the lower toughening temperature. This is a question in which the personal element and experience of the heat-treatment man would be paramount.

**Influence of the Carbon Content.**—In respect to the selection of the steel in relation to the treatment there remains the consideration of the influence of the carbon content. Carbon not only intensifies the effect of the rapid cooling (hardening), but it also directly augments the brittleness of the steel. Or, to put it in other words, the greater the carbon content the greater the hardening strains, and the lower the ductility which can be obtained with a stated tensile strength. It is therefore usually desirable to provide a steel with as low a carbon content as will give the desired results.

**Toughening vs. Annealing.**—It is only within comparatively recent years that the toughening process with its attendant sorbitic structure has been used and understood. Previously, annealing was generally the cure-all for brittleness and a strained condition of the steel. Pearlite—produced by annealing—on account of its entangled structure, gives a large measure of ductility; but also gives a minimum tenacity. The appearance of sorbite, however, is even more entangled than pearlite; sorbite is far superior to pearlite in tensile strength and especially in elastic limit. Thus by obtaining a sorbitic steel by suitable treatment, almost as much ductility, greater working strength, greater dynamic strength, and—by being able to use a lower carbon steel—less brittleness may be obtained than in a pearlitic or annealed steel.

**Standardization of Results.**—With the same degree of hardening, and if the reheating has been uniform and thorough at a given temperature, the physical results will be comparatively the same for material of equivalent section and the same composition. That is, the product will be standard for standardized treatment. Further, in order to get standard results with steel purchased under the same general specifications (i.e., each chemical constituent within certain limits), the toughening temperatures may be varied according to the chemical composition. To illustrate: the following heats of steel of varying chemical composition and made by several steel companies were manufactured into a certain product which, when heat treated, required an elastic limit of 85,000 to 95,000 lbs. per



square inch, and an elongation of not less than 16 per cent. in 2 ins. In spite of the varying carbon, manganese, chrome and nickel contents, the toughening temperatures (maintained within 5° F. under or over) were so adjusted as to give the desired results. Thousands of pieces, some weighing as much as 200 lbs., all fulfilled, by actual test, the standard physical specifications.

Carbon.	Manga- nese.	Phosphorus.	Sulphur.	Chrome.	Nickel.	Toughen- ing Temp. Deg. Fahr.
0.16	0.43	0.015	0.017	0.62	1.82	1050
.185	.44	.010	.015	.57	1.56	975
.20	.43	.009	.016	.64	1.74	1025
.20	.46	.011	.017	.40	1.56	950
.21	.48	.015	.015	.60	1.77	1050
.21	.50	.017	.014	.67	1.84	1075
.23	.50	.016	.018	.65	1.73	1075
.245	.53	.015	.020	.62	1.79	1120
.25	.50	.011	.019	.64	1.40	1140
.26	.43	.010	.018	.60	1.65	1100
.27	.49	.015	.021	.63	1.79	1150
.28	.51	.008	.011	.41	1.57	1120

**Quench-Toughening.**—A process which has been used considerably for the treatment of large forgings of uniform section, such as heavy axles, is that of heating as usual for hardening and then quenching in oil for a specified number of seconds, followed by air cooling. The oil quenching affects the steel to a certain depth, but still leaves a considerable amount of heat in the forging when removed from the bath. As the forging cools in the air this heat from within will toughen or “soften” the steel affected by the quenching. In order to obtain equivalent results under varying conditions the number of seconds required for immersion in the oil of a piece of given size must be determined by experiment and strictly adhered to. Forgings treated by this process are characterized by a soft or annealed core, with a progressively toughened outer part.

**Physical Results.**—In subsequent chapters will be given results obtained in actual practice by the use of various toughening temperatures for different grades of steel.



## CHAPTER VI<sup>1</sup>

### CASE CARBURIZING

**Object of Case Hardening.**—The object of case hardening or partial cementation is the production of a hard wearing surface (the “case”) on low carbon steel, and at the same time the retention or increase of the toughness of the “core” of the metal. The process may be roughly divided into two distinct periods. First, the carburization or impregnation of the surface by which the carbon content is sufficiently raised—dependent upon the demands of the work—so as to give a steel capable of taking on very great surface hardness. Second, suitable heat treatment which shall develop the properties of both case and core. The complete operation should not only result in the obtaining of a very hard case, but also and simultaneously in the realization of special mechanical properties in the core—more especially that of non-brittleness. Briefly, the aim is to have a piece of steel which shall possess a minimum fragility and a maximum surface hardness.

**Requirements for Case Carburizing.**—In order to obtain a case rich in carbon, the metal is heated in the presence of a body which is capable of delivering this carbon, by more or less complex reactions, which is then dissolved by the steel. Aside from the use of gases in the newer processes involving such factors as pressure, quantity, etc., there are four main factors which must be considered in the carburizing operation:

1. The solvent: that is, the steel;
2. The product to be dissolved, or more exactly, the compound capable of delivering the carbon, i.e., the cement;
3. The temperature;
4. The time of contact between the steel and the carburizing agent.

<sup>1</sup>Cuts by Giolitti from “The Cementation of Iron and Steel,” by courtesy of McGraw-Hill Book Co.; references made in this chapter to investigations by Giolitti are also from the above.

## THE STEEL

**The Steel.**—The character of the initial steel used for case carburizing depends largely upon the fact that one of the main desires is to eliminate brittleness in the core. We have seen that any increase of carbon, other conditions being equal, will increase the brittleness, particularly when the carbon content is raised to over about 0.25 per cent. Further, as practically all commercial carburizing processes involving case hardening are followed by one or more hardening operations, it follows that the use of a steel with a higher carbon content will also increase the brittleness through quenching. For these reasons it is therefore necessary to keep the carbon content of the steel to be carburized quite low, preferably under 0.25 per cent. for straight carbon steels. In fact, the best French practice is to demand a carbon content of not over 0.12 per cent., further qualified by the specifications that the core after quenching shall give a tensile strength of about 54,000 lbs. per square inch and not to exceed 85,000 lbs., together with an elongation of 30 per cent. in 100 mm. (3.94 ins.).

However, one of the important and often unsatisfactory results of using an extra-soft steel is the difficulty encountered in machining (before carburizing). If the carbon is extremely low the steel is very apt to tear, and thus increasing the amount of grinding after hardening—in order to obtain a perfectly smooth surface. For this reason, the general American practice is to adopt a carbon content about midway between the extreme upper and lower limits and specify a steel with about 0.16 to 0.22 per cent. carbon. The higher carbons also give increased stiffness to the core which, in some cases, is necessary.

It is generally recognized that the carbon content, at least up to some 0.50 per cent., has no influence upon the velocity of penetration of the carburization, i.e., the depth of carburization which will be obtained for a given length of exposure.

On the other hand, the initial carbon content of the steel will have a decided influence upon the maximum carbon content which will be obtained in the case; the higher the initial carbon, the higher the maximum carbon concentration in the case.

**Manganese.**—It is considered the best practice, in general, to require a low manganese content with about 0.30 to 0.35 per cent. as the maximum. It should be remembered that the case which will be formed during the carburization will be characteristic of

a high-duty tool steel and will have the properties of such. Thus manganese will increase the hardness of the case (and also of the core) and will make the steel as a whole more sensitive to rapid cooling. In spite of this, it is often customary, especially in British practice, to use a manganese content of about 0.70 per cent.—and in some cases even up to 0.90 per cent.—in order to obtain greater stiffness in the core. Manganese at such percentages also increases the brittleness produced by long heating during carburization, and diminishes the efficacy of the regenerative quenching. These last named points are also true when the silicon is much over 0.30 per cent.

**Other Impurities.**—It is self-evident that the content of phosphorus and sulphur in the initial steel should be just as low as is possible. Slag, blow-holes, segregation, and all other impurities and imperfections should be entirely absent from steels for case hardening.

#### THE CEMENT

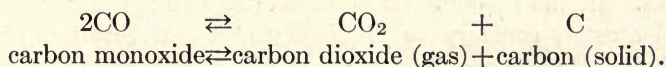
**Direct Action of Carbon.**—Carburization by its very nature requires the presence of free carbon in some form or other, either as a solid body, or as some gas which will produce free carbon by its decomposition. The mere presence of free carbon in contact with iron, however, will not satisfy the conditions necessary for commercial carburization. Although it has been shown scientifically that carbon alone, without the intervention of any gas, will carburize iron if it is kept in contact with it for a sufficiently long time and at a sufficiently high temperature, this *direct action*, as far as industrial results are concerned, is negligible. That is, the ordinary forms of solid carbon, such as wood charcoal, sugar charcoal, etc., exercise *directly* on iron but a very slight carburizing action in the *absence of gases*.

**Action of Gases.**—It will be noted that emphasis has been laid upon the “direct action” in the “absence of gases.” This at once leads to the question as to what is meant by the action of gases, and which, in turn, involves the mechanism of cementation itself. It is a well-known fact that when steel is heated, the “pores of the steel are opened”—to use the vernacular expression—it becomes easily permeable to gases, and the surrounding gases diffuse into the steel. This is true whether the steel is heated in the ordinary atmosphere, when the gases consist of nitrogen and oxygen, or whether it is heated in some specially prepared atmosphere, such as carbon monoxide,



illuminating gas, etc. The main fact to be realized is that the gases do penetrate into the steel, although the effect of the gases will depend upon the composition of the gas, besides such other factors as pressure, temperature, and so forth. Thus, recognizing that the direct action of carbon—that is, the carburizing results obtained by mere contact of carbon with iron—is commercially negligible in the absence of gases, it is evident that carburization must be intimately related to the *presence* of gases. In other words, the gases (or, more exactly, certain gases) must in themselves act as the *carrier or vehicle* for the carbon. That this carrier action, or transporting of the carbon, has not been definitely recognized or determined until recently has been due to the fact that practically all of the solid cements generate the necessary gases through their own decomposition and interaction with the occluded air. Further, the intense and critical study of this action has been developed only by the research work in connection with the newer processes of case carburizing by means of gases alone.

**Action of Oxygen.**—As a typical example of this diffusion and its effect we may consider any ordinary carburization process in which wood charcoal is used as the base cement. When the carburizing material and articles are packed in the carburization boxes there is necessarily a considerable quantity of air also occluded with the particles of the cement. Under the influence of heat the oxygen of the occluded air will react with the carbon or charcoal to form carbon monoxide gas, which has the symbol CO. Then, as the temperature of the box and contents increases to the temperature of the carburization proper, these gases of carbon monoxide permeate or diffuse through the surface and outer section of the steel. At the same time, by catalytic action, the carbon monoxide gas decomposes when it comes in contact with the steel and sets free a part of the carbon it contains. This decomposition may be represented by the reversible reaction



Thus, as the gas diffuses into the mass of the steel it continues to decompose, setting free new quantities of carbon within the steel. This carbon, at the proper temperatures of carburization, passes directly into solution in the steel and forms a true steel proper. The reaction above, being reversible—as might be shown—will continue indefinitely under suitable conditions, the charcoal regenerating the

supply of carbon monoxide. Further, while it is a well-known fact that carbon monoxide, acting alone on iron, will deposit free carbon on the *surface* of the iron, this action takes place only at temperatures *lower* than those ordinarily used for commercial cementation. In other words, the carburizing action of charcoal as used in practice is not due to the direct action of the carbon, but is due (under the conditions named, which of course may be modified by the presence of other gases or components of the cement) entirely to the specific action of carbon monoxide as a gas.

**Nitrogen.**—The action of the oxygen of the occluded air being accounted for, the accompanying constituent nitrogen must be considered. Although it has been shown that during carburization the nitrogen may and will diffuse in small amounts into the steel, it is now certain that the presence of pure nitrogen does not increase, except to a minimum extent, the carburizing action of free carbon. In fact, instead of nitrogen being requisite—as many still believe—it may even exert a pernicious effect. LeChatelier has suggested that the increase in brittleness sometimes observed in those parts of the steel subjected to cementation, but which the carburization has not even reached, may be due to this nitrogen. It might be added that this deleterious nitrogenizing theory is further supported by experiments along other lines—particularly in the apparent cleansing effect for nitrogen of the titanium additions to steel during manufacture. Another general effect of nitrogen gas is to reduce the cementing action of the carbon monoxide mentioned by its diluting the carburizing gas. For practical purposes of carburization, however, the action of nitrogen in the presence of free carbon is too slight to influence commercially the results obtained with a given cement, unless actually added (in gaseous cementation) as a diluent.

**Carbonates.**—The ash of the carbonaceous matter may also contain carbonates of the alkali or alkaline-earth metals. Or these carbonates, such as barium carbonate, may be added directly to the cement. In the light of the most reliable and recent researches it would appear, contrary to previously accepted theories, that the activity of these carbonates is not due to the formation of volatile cyanides by the action of the nitrogen of the occluded air, but *exclusively* to the formation of *carbon monoxide* produced by the action of the hot carbon on the carbon dioxide produced through the dissociation of the carbonates. Thus the effect of such carbonates is similar to that produced by carbon monoxide under similar conditions.

**Cyanides.**—The most maligned constituents of cements are the cyanogen group. In the past it has been thought that the derivatives of this group played the chief part in carburization processes. This, however, has been strongly disproved by Giolitti, who admirably explains the matter as follows: That cyanogen and the more or less volatile cyanides can cement iron intensely is beyond doubt. Moreover, it is well known that fused potassium and potassium ferrocyanide are used in the pure state to obtain thin and strongly carburized zones (as in superficial carburization or cyanide hardening). In industrial practice the cyanides do not exist already formed, but may be formed in very small quantity by the action of the nitrogen of the air (occluded in the cement) on the carbon used and on the small quantities of alkali constituting a part of the ashes of this carbon. Although the formation of small quantities of alkali cements cannot therefore be wholly avoided in industrial carburization with carbon as a base, the part which is played by these traces of volatile cyanides is *certainly negligible* in comparison with that of the carbon monoxide formed by the action of the air on the carbon used as cement.—He then submits conclusive proofs to substantiate these statements.

**Carbon Monoxide Gas.**—Carburization carried out by the use of carbon monoxide gas alone will give a mild or gradual carburization in which the maximum carbon content is comparatively low—not usually reaching the eutectoid ratio even at the periphery—and which diminishes progressively and in a uniform and slow manner passing from the surface of the case toward the interior of the carburized piece. Carburized zones of this type correspond always and only to carburization carried on with pure carbon monoxide, a concentration-depth diagram of which is shown in Fig. 61. On account of its definite chemical composition and simplicity of action, the general behavior of carbon monoxide is known within almost exact limits. The carburizing action is easily regulated, and the case may be obtained with certainty with any kind of steel in commercial use.

When working under suitable conditions, carbon monoxide—either alone or with a mixture in which the carbon monoxide can exercise its maximum carburizing action—will give the greatest velocity of carburization, i.e., the depth reached in a given time by the carburized zone. This depth is also a direct function of the time or length of exposure.

All other conditions being equal, the higher the temperature of



carburization using carbon monoxide, the smaller will be the maximum carbon content of the case. Similarly, the lower the pressure of the carbon monoxide, the smaller the maximum carbon content; and the greater the quantity of pure carbon monoxide gas coming in contact with a unit of surface, the greater the carbon concentration.

Under suitable conditions, carbon monoxide gas will deposit no carbon on the surface of the steel being carburized, so that there is little difficulty in keeping the surface bright. Further, the use of carbon monoxide reduces to a minimum the deformations and variations in volume due to the carburizing processes. Carbon monoxide also lends itself in obtaining a good protection of the parts of the steel which it is not desired to carburize.

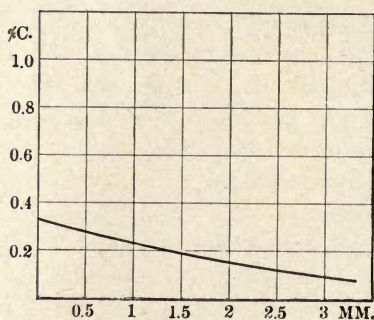


FIG. 61.—Carburization at 2010° F. for Ten Hours with Carbon Monoxide. (Giolitti.)

**Hydrocarbons.**—Most of the forms of solid carbon used in practical carburization are not pure, but may contain organic residues not wholly decomposed, or considerable proportions of ash rich in certain carbonates. Thus charred bone, charred leather and similar organic products often used, will, under the influence of heat, evolve hydrocarbons. These hydrocarbons, by more or less complex reactions, deposit the excess of finely divided carbon which they contain on the surface of the metal; and this, in turn, being in perfect contact with the metal, at high temperatures may cause a *direct* carburization by contact. But further and vastly more important than this direct action of the carbon deposit on the surface of the metal, is the carburization by means of the specific action of the gas itself, although of course depending more specifically upon the exact conditions of carburization. In a manner somewhat analogous to

that of the decomposition of the carbon monoxide within the steel, yielding carbon directly to the steel, the hydrocarbon gases will also diffuse into the steel and there yield carbon. Hydrocarbons therefore also act as carriers for the carbon and effect a carburization due to the specific action of the gas.

Carburization with pure hydrocarbon gases give cases of a type corresponding to Figs. 62 and 63, and to Fig. 64. These are characterized on slow cooling by (1) a layer or zone of hyper-eutectoid steel consisting of free cementite and pearlite; (2) by a layer of eutectoid steel, generally quite thin; and (3) by an internal layer of hypo-eutectoid steel. The main points to be noticed are, that

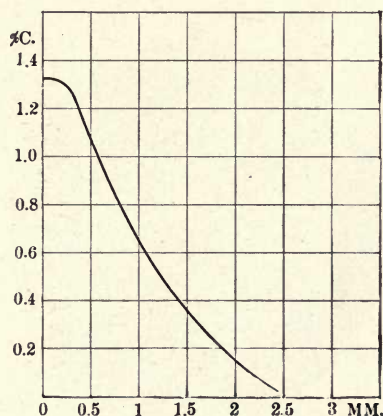


FIG. 62.—Carburization at 1830° F. for Five Hours with Ethylene. (Giolitti.)

the case contains a structure with greater than 0.9 per cent. carbon, and more emphatically, that the concentration of the carbon often diminishes in a markedly non-uniform manner or discontinuity. Zones of this type are always found in carburizations carried out with hydrocarbons; they also are typical of carburizations obtained with many of the solid carburizing compounds used in commercial work in which the action of the hydrocarbons greatly predominates, or in the presence of cyanides (superficial cementation).

Of the specific action of the gaseous hydrocarbons, we may make the following remarks. The depth or velocity of penetration increases, similarly to carbon monoxide, with the time of exposure. In the case of carburization with ethylene and methane, the cemented zones obtained in a definite time, although likewise increasing

markedly in thickness with rise in temperature, other things remaining constant, maintain about the same concentration and the same distribution of the carbon in the three zones—thus differing widely from carbon monoxide. In contrast with the use of these pure gases, the use of hydrocarbons in practice presents a different aspect, especially when compared with the use of carbon monoxide in practice. Contrary to the simplicity of the reactions which always characterize the cementation by carbon monoxide, the complexity of the reactions with hydrocarbons increases enormously in industrial work. The gas in such instances does not consist of a single, chemically definite hydrocarbon, but of a mixture of various hydrocarbons. If we work at a comparatively low temperature, such as at, or slightly

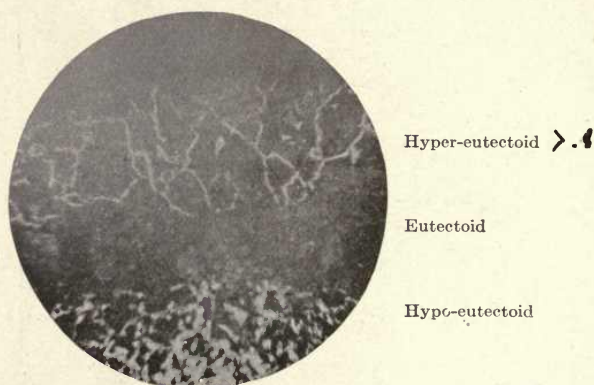


FIG. 63.—Carburization with Hydro-Carbons.  $\times 25$ . (Bullens.)

under, the upper critical range, the process is slow and non-uniform. At the high temperatures generally used, cemented zones of excessively high carbon are always produced. The same complexity of reactions make it difficult, in practice, to work with a cement having hydrocarbons as a base, either as a mixture of solids in the carburizing box, or as gases in the newer processes, in such a way as to obtain well-defined results. Thus the use of such hydrocarbons is not advantageous where a certain value of maximum concentration, combined with a definite distribution of that carbon, is necessary in carburized steels in which a considerable depth is desired.

**Enfoliation.**—All those who have had much to do with case hardening and its products are familiar with the flaking, chipping, or even peeling off of parts of the case from the remainder of the steel.



These fractures are entirely different from those occurring in homogeneous high-carbon hardened steels. While in the latter the fractures always have a characteristic conchoidal form, in case-hardened steels the chipping or enfoliation always takes place along a line corresponding to the separation of two zones exhibiting markedly different structure or "grain." A microscopic and chemical investigation brings out the fact that this line or plane of weakness characterizes the separation of the hyper-eutectoid zone from that of the hypo-eutectoid zone, or at a carbon content corresponding to that of about 0.90 per cent. Further, this plane of weakness corresponds to a discontinuity in the concentration or distribution of the carbon

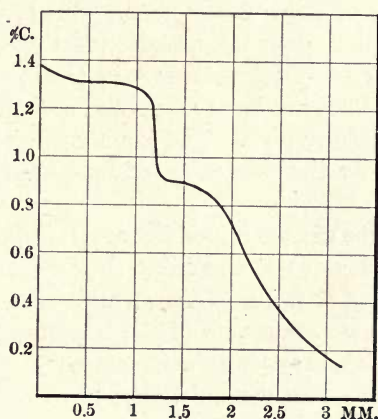


FIG. 64.—Carburization at 1920° F. for Four Hours with Ethylene. (Giolitti.)

which is characteristic of carburized zones of the hydrocarbon type previously described.

It is now evident that, in order to eliminate the possibility and dangers of this enfoliation, we must

- (1) obtain a gradual and progressive change in the distribution of the carbon so that it will vary from the minimum of the core to the maximum at the surface of the case, and in no place exhibit the phenomenon of discontinuity;

- (2) eliminate the possibility of discontinuity at the eutectoid by keeping the maximum concentration of the carbon at or below 0.90 per cent. carbon (thus eliminating the hyper-eutectoid zone);

- (3) and in any case, modify by suitable heat treatments the structure obtained by carburization.

**Maximum Carbon Concentration.**—Now while we have under (2) advised the eutectoid carbon ratio as a means of preventing enfoliation, it must not be at once concluded that enfoliation is the direct sequence of increasing the carbon concentration maximum to over 0.9 per cent. Such is not the case if the *proper heat treatment* methods are employed. Unfortunately, however, the majority of commercial plants employing case hardening do not either understand, or are unable to put into practice, the methods which are necessary when the carbon content of the case runs beyond 0.9 per cent. carbon. That such high carbon contents are undeniably advantageous in many instances where it has been generally thought that their use was impossible will also be shown, as will the so-called “secret” processes of treating the steel. But for plants which are unable to employ the necessary metallurgical skill and appliances, it will be far better to adopt such case-hardening processes as will turn out a good product having a maximum carbon concentration in the case of about 0.9 per cent. The further advantages of this will be brought out under the discussion of heat-treatment methods in Chapter VII.

**Intermediary Type of Carburized Zone.**—Recognizing under these conditions the validity of not exceeding the eutectoid limit, and the obvious advantages of preventing discontinuity between the core and the surface of the case regardless of the maximum carbon content, it is evident that we must obtain a cemented zone intermediary between those of the two general types, previously described. In other words, the type of case must have the principal characteristics of the carbon monoxide type, but which are modified—by increasing the carbon content—by cements typical of the hydrocarbons, or other suitable procedure.

**Carbon Monoxide Plus Hydrocarbons.**—From the results of experiments carried out with carbon monoxide plus specific amounts of hydrocarbons, Giolitti shows that the additive effect of the latter, as compared with those carried out with pure carbon monoxide, may be summed up as follows: “The addition of small quantities of volatile hydrocarbons to carbon monoxide merely raises the concentration of the carbon in the external layers of the cemented zones above the value which would result from the use of pure carbon monoxide under identical experimental conditions. This increase is greater the larger the proportion of the hydrocarbon contained in the gaseous mixture, as long as this proportion does not reach a value such that the velocity with which the free carbon is formed

by the decomposition of the hydrocarbon does not surpass the velocity with which this carbon passes through the stage of carbon monoxide into solution in the iron. From this limit the excess of carbon which is liberated begins to deposit on the steel and the concentration of the carbon in the external layers of the cemented zone reaches the maximum value corresponding to that which is obtained by cementing with solid cements, or with cements which behave as such, and from this point on, the concentration and the distribution of the carbon in the cemented zones no longer vary markedly, even if the proportion of the hydrocarbon increases greatly."

"From what precedes it is evidently possible to obtain, by means of mixtures of carbon monoxide and vapors of volatile hydrocarbons, cemented zones in which the maximum concentration of the carbon

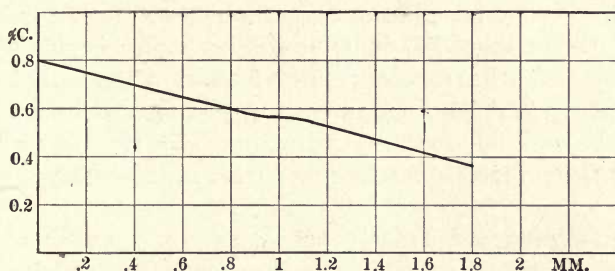


FIG. 65.—Cemented Zone, Intermediate Type, Carburized with Carbon Monoxide Plus 3.1 per cent. Ethylene. (Giolitti.)

in the external layers has a definite value, lying between a minimum corresponding to that which would be obtained by working under the given conditions with pure carbon monoxide, and a maximum which would be obtained by working with vapors of the hydrocarbon alone. This is achieved simply by using gaseous mixtures containing a proper proportion of hydrocarbon varying with the conditions under which cementation is to be effected, such as temperature, pressure, relation between the velocity of the gaseous current and the surface of the steel to be cemented, etc."

An example of this is shown by the concentration-depth diagram in Fig. 65, the results of which were obtained experimentally by cementing 0.26 per cent. carbon steel cylinders for four hours at a temperature of 1830° F. in a mixture of carbon monoxide with 3.1 per cent. of ethylene. It will be noted that the carbon decreases progressively and in a slow and uniform manner, but that the addi-



tion of the hydrocarbon has raised the maximum carbon content up to nearly the eutectoid ratio. Thus, in this case, there has been produced a carburized zone of an intermediary type which fulfils the requirements stated for the avoidance of enfoliation.

Following along these lines of using a gaseous mixture consisting of certain proportions of carbon monoxide gas and the volatile hydrocarbons, several industrial methods have been worked out, and which have given excellent satisfaction. The application of the same theory is also applicable to the commercial solid cements in which the necessary gases are evolved during the heating operation, but on account of the greater lack of control the variations to be obtained are necessarily of considerable extent.

**Carbon Plus Carbon Monoxide.**—As we have stated, the carburizing action of solid carbon in the absence of all gases is commercially negligible. But by introducing oxygen which will form the gaseous vehicle (carbon monoxide), or by adding carbon monoxide directly, the presence of solid carbon greatly intensifies the carburization. Thus, similarly to definite mixtures of carbon monoxide plus hydrocarbons, the desirable form of the intermediary type of carburized zone may be obtained by carbon monoxide in the presence of solid cements.

By varying the various factors of temperature, time of exposure, pressure of gas, etc., the use of a mixed cement may be varied within wide limits, and with the production of a hyper-eutectic zone if so desired. This latter comes into great practical use when it is desired to produce zones of considerable width. Co-ordinated with this is the use of carbon monoxide as an "equalizer," that is, by first carrying out the carburization process in the usual way (with mixed cements), the maximum concentration of the carbon may be made quite high; this is then followed by the use of carbon monoxide alone (without the presence of granular carbon). By these means the concentration of the carbon may be lowered—by the distributive action of the carbon monoxide, to such maximum concentration as may be desired. This is graphically shown in Fig. 66, by Giolitti. The steel used was of the composition:

	Per cent.
Carbon .....	0.12
Manganese .....	0.47
Phosphorus.....	0.03
Sulphur .....	0.02
Silicon.....	0.06

Curve *a* shows the concentration depth after carburization for ten hours at 2010° F. with mixed cement. Curve *b* represents the results after heating the preceding for five hours at the same temperature in "isolated" carbon monoxide. Curve *c* gives the results after another five hours heating at the same temperature in "isolated" carbon monoxide. Thus we see that the curves have undergone a gradual change in form and position due to the action of carbon monoxide alone. Such methods as these will permit of the elimination of the dangerous hyper-eutectoid zone, and at the same time give

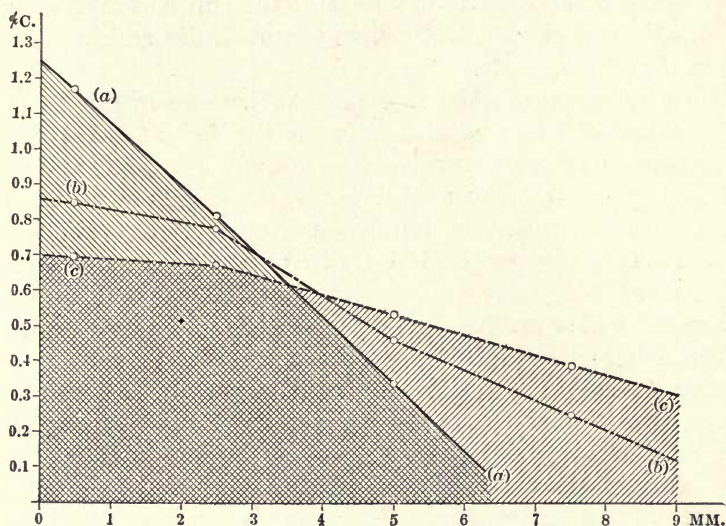


FIG. 66.—Distributive Action of Carbon Monoxide. (Giolitti.)

all the benefits to be obtained from a carburized zone of the intermediate type previously described.

#### TEMPERATURE AND TIME FACTORS

**Solution of the Carbon.**—We have seen how certain gases, by diffusing into the steel, precipitate free carbon within the steel. Now this carbon, under suitable conditions, may be dissolved at once by the iron, forming a true steel. It is evident that the solubility of this carbon (or carbide) must depend upon the allotropic condition of the iron, which, in turn, will depend upon the temperature. As we have explained in previous chapters, iron may be held in the alpha, beta or gamma state. Thus, if a piece of normal 0.2 per cent. carbon



steel is heated, none of the cementite which is mechanically mixed with ferrite (iron) to make up the mechanical mixture pearlite is affected until the lower critical temperature of about 1350° F. is reached. At this temperature the iron of the pearlite, previously in the alpha condition, changes into gamma iron and dissolves the cementite, the two forming a solid solution or austenite. In other words, it is necessary for the iron to be in a higher allotropic condition than that of the alpha stage in order to dissolve carbon (or carbide). As the temperature of the steel is progressively raised, more and more of the excess iron is dissolved by the austenite, until at the Ac3 range the whole mass of the steel consists of austenite and has all the iron in the gamma state.

Thus we see that while it is possible for carburization to take place at temperatures varying between the Ac1 and Ac3 ranges, the carburization must necessarily be not only slow, but also irregular and non-uniform. In other words, the minimum temperature which should be used in industrial carburization should not be lower than the upper critical range of the initial steel to be carburized.

**Depth of Penetration.**—All commercial carburizing processes must provide a depth of case which will satisfy the requirements of the specific use to which the steel will be put in practice. Thus many parts will only require a depth of case of say  $\frac{1}{64}$  or  $\frac{1}{32}$  of an inch, or if grinding is necessary, this may be increased to  $\frac{1}{16}$  of an inch; other parts, such as armor plate, may require a considerable thickness. With a definite depth of case in view, economic considerations require that the velocity of penetration shall be definitely known in relation to the factors of time and temperature, the nature of the carburizing agent, and—in the case of gases—such other factors as pressure, quantity of gas, etc.

The penetration of carbon (differentiating this *depth* of penetration from the *distribution* of the carbon) increases with the temperature and with the time of exposure, but not always in direct proportion to these two factors. Given a definite temperature and carburizing compound, it may be said in general that the carburization commences and continues at a comparatively high rate of speed until the outer layers are saturated with carbon—dependent, of course, upon the nature of the cement; there is then a drop in the rate of carburization, varying according to the temperature, and this in turn is followed by a velocity of penetration which seems to be more nearly proportional to the length of exposure.



These facts are shown graphically in Figs. 67 and 68, the former illustrating this velocity of penetration particularly for short exposures, while the latter emphasizes the effect of long continued heating. In each case the experiments were carried out under conditions usually adopted in industrial establishments. The bars of soft steel were allowed to soak at the stated temperatures for definite lengths of time and the penetration was then measured. The results from which these graphs were plotted were reported, in the first instance,

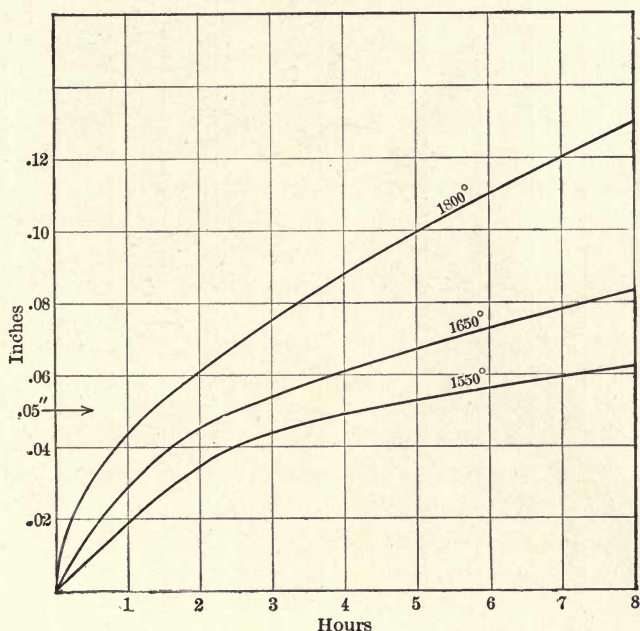


FIG. 67.—Velocity of Penetration, Short Exposures.

by a company using a cement of the barium carbonate-carbonaceous type, and in the second case by Giolitti, using a common commercial cement consisting of ground-wood charcoal treated with 5 per cent. potassium ferrocyanide and mixed with an equal weight of barium carbonate.

In the case of the first compound it is interesting to note that there is a decided decrease in the relative rate of penetration when the depth of case reaches approximately 0.05 in. This cycle appears to take place in the same order at all temperatures used, with the difference that the relative speeds of penetration are higher

at higher temperatures, although not proportionally so. Thus we may coin a phrase and call this depth of 0.05 in. the "critical penetration" of this individual compound. Considering the depth of penetration only, and disregarding other economic and technical factors which may enter into consideration, it is evident that this particular compound may be used to good advantage when a case corresponding to about 0.05 in. is desired. To this depth the steel will be carburized at a maximum speed or velocity, and there-

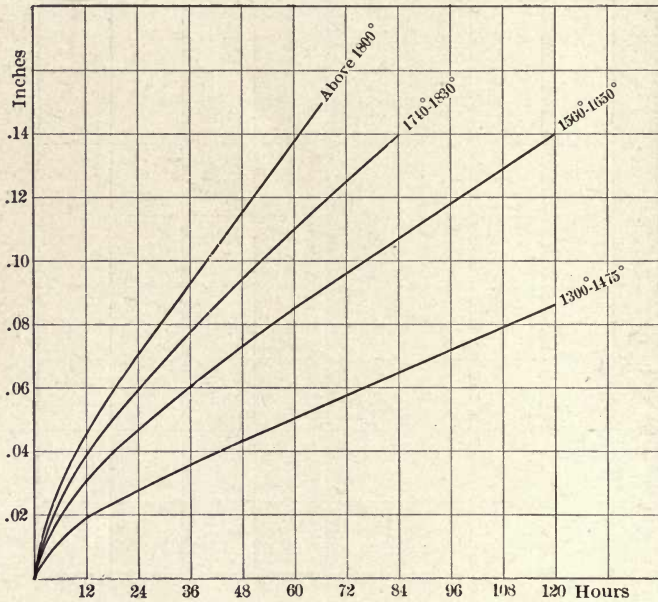


FIG. 68.—Velocity of Penetration, Long Exposures. (Giolitti.)

fore at the minimum furnace or heating cost. With this particular compound simply as an illustration, any other commercial carburizing compound might be studied from the practical side for the determination of this critical depth of penetration, and use made of the results to good advantage in reducing operation costs.

The influence of temperatures of carburization under the upper critical range upon the depth of penetration and the maximum carbon content is also brought out by a comparison of Figs. 69 and 70. These photomicrographs represent the effect of cementation upon a 0.11 per cent. carbon steel carburized for one hour in a mixture of

charcoal and barium carbonate, but at different temperatures. Fig. 69 shows the results of a temperature under the A3 range; Fig. 70 the cementation at a temperature considerably over the A3 range. The practical value is self-evident.

**Liquation.**—Sudden variations in the concentration of the carbon in the cemented zone may be manifested when intense carburization is effected at high temperatures, and the carburized pieces are allowed to cool slowly through a more or less wide interval of tem-



FIG. 69.—Carburization of 0.11 per cent. Carbon Steel at a Temperature under the Upper Critical Range with  $\text{BaCO}_3$  and Charcoal, for One Hour. (Nolly and Veyret.)



FIG. 70.—Carburization of 0.11 per cent. Carbon Steel at a Temperature Considerably Over the Upper Critical Range with  $\text{BaCO}_3$  and Charcoal, for One Hour. (Nolly and Veyret.)

perature before being quenched. This variation consists of a true liquation of the cementite (and of the ferrite) during their segregation from the solid solution. Take, for example, the diagrams in Figs. 71 and 72, representing the results obtained by carburizing a 0.26 per cent. carbon steel for four hours at  $1830^\circ \text{F.}$  in ethylene, with the difference, however, that the carburized steel represented by Fig. 71 was cooled—during 32 minutes—to a temperature of  $1380^\circ \text{F.}$  and then quenched, while that of Fig. 72 was quenched immediately following carburization from that temperature ( $1830^\circ$ ).

Comparing the two diagrams we see that, while the concentration of the carbon in Fig. 72 *decreases* continuously and uniformly as we



proceed from the surface towards the core, that in Fig. 71 shows a marked *increase*, followed by a very rapid decrease, before it exhibits

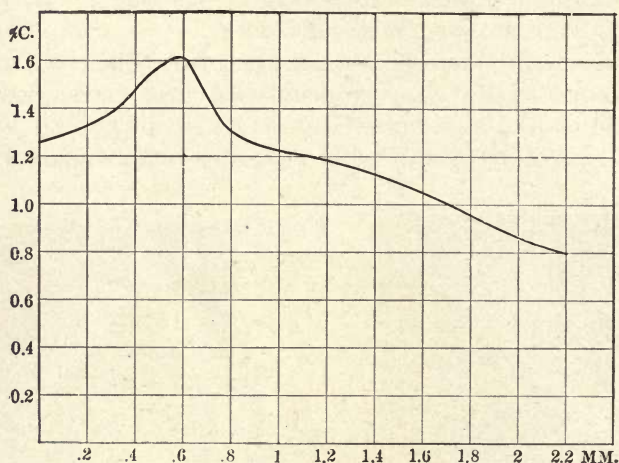


FIG. 71.—Liquation of Cementite through Slow Cooling. (Giolitti.)

that gradual decrease which characterized the first case. As the carburization proper was identical in both cases, it is evident that

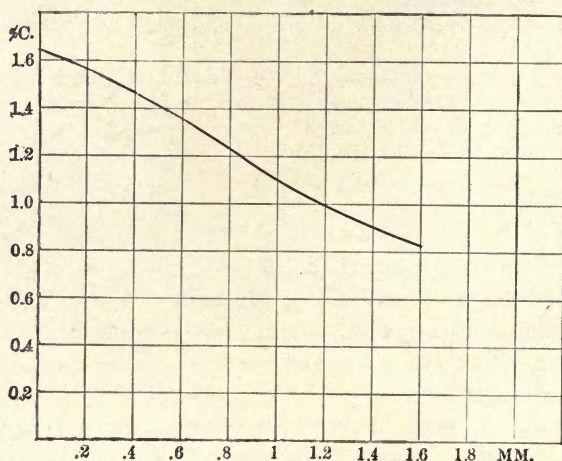


FIG. 72.—Prevention of Liquation by Quenching. (Giolitti.)

the discontinuity in the carbon distribution must be due to the difference in the rate of cooling following the carburization proper.

Thus we see that the liquation, or accumulation, of the cementite in the external layers will tend to emphasize the line of demarkation between the hyper- and hypo-eutectoid zones. And this, in turn, will magnify the dangers of enfoliation. Fig. 73 is a photomicrograph from a piece of carburized steel which failed in service; the cause of enfoliation in this case is undoubtedly due to this phenomenon of liquation.

This is another reason why those processes of carburization should be used which will avoid the formation of the hyper-eutectoid zone,

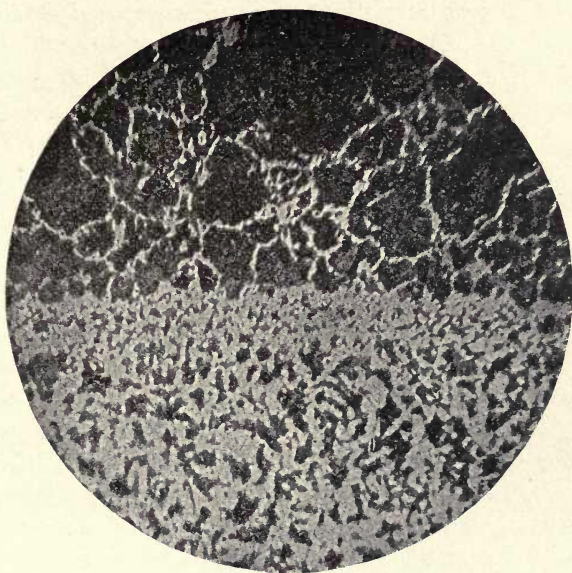


FIG. 73.—Failure Due to Liquation. (Giolitti.)

and thus eliminate the possibility of enfoliation through differences in carbon distribution caused by accumulation of the free cementite. However, if cements which give carburized zones of the hydrocarbon type are used, it is apparent that this accumulation may be avoided by quenching from the temperature of carburization. Although this is possible in the newer processes of using either a gaseous mixture or a mixed cement, it is manifestly impossible under the older methods of using solid cements. We will shortly describe methods of heat treatment by which the effect of the cementite accumulation may be corrected in the majority of instances, as well

as giving reasons why quenching from the temperature of carburization—when it is 1750° F. or more—is technically bad.

**Oscillating Temperatures.**—There is still another effect of temperature which should be mentioned in this connection on account of its action in many industrial carburizing processes. This is the effect of non-uniform or oscillating temperatures during carburization, so often met with in practice. Without going into the theoretical explanations involved, it has been shown by Giolitti and Scavia that, where under normal conditions the formation of free cementite cannot take place, by carrying out the carburization under identical conditions but with variable temperatures oscillating within definite intervals, the occurrence of free cementite will result. The industrial importance of this is evident. In the first place it explains the abnormal increase in free cementite which is sometimes met with in practice in which the normal nature of the carburization should produce cemented zones of the intermediate type and the absence of free cementite, besides demonstrating the necessity of maintaining *uniform* temperatures throughout the whole carburization within a very close range. And in the second place it furnishes a means of carrying out the heating during carburization in such a way as purposely to cause, with certainty, the formation of free cementite when it is desired to obtain cemented zones capable of taking an exceedingly high degree of hardness by quenching without its being necessary that their brittleness be reduced to a minimum.

**Temperature Factors.**—Although much has been said and written concerning the effect of temperature upon carburization, the majority have confused the *velocity or depth* of the carbon concentration with the *maximum concentration and distribution* of the carbon. While it has been shown that the depth of penetration is, in general, a direct function of the temperature with all commercial carburizing mixtures, the same is not entirely true of the maximum concentration of the carbon. In fact, through the study of pure gases such as we have indicated, it has been shown that in the case of carbon monoxide alone the maximum concentration of the carbon actually decreases, other things being equal, with increase in the temperature of carburization.

In the cases of the newer processes involving the uses of gases or a mixed cement, the effect of such temperature on the maximum concentration and distribution of the carbon may be practically varied at will by a change in the other factors previously mentioned. In other words, on account of the almost absolute control with which



such processes of carburization may be regulated, the actual effect of the temperature is minimized and does not play the important part which is manifested in the older processes involving the use of solids alone.

**Influence of Temperature on Different Cements.**—The complexity and lack of control of the reactions involved in the use of solid cements make the factor of temperature extremely important. Thus some cements, such as charcoal plus barium carbonate, which at the lower temperatures give "gradual" or "mild" cases, at the higher temperatures may act as "sudden" or "quick" cements. A consideration of the common solid cements (of which we are now speaking) as used in general commercial work would tend towards the conclusion that their action, on the whole, is more gradual at the lower temperatures than at the higher temperatures. Further, it might even be said that, other things being equal, the higher the temperature of carburization the higher will be the maximum carbon concentration in the case. Although these statements may not hold good for all instances in which carbon is used as the base, their practical working out is generally evidenced in the general average of thin cemented zones found in commercial case hardening.

**Low Temperature Carburization.**—Now as the majority of case-hardened products require the elimination of brittleness, both in case and core, and as the use of "gradual" cements at the lower temperatures of carburization will advance that condition of affairs (i.e., the formation of cemented zones of the intermediate type, showing the absence of the hyper-eutectoid-zone, and a gradual distribution of the carbon concentration from the external surface of the case to the core) the use of the lower temperatures of carburization is coming more and more into vogue. That is, the tendency is to use moderate heats and maintain them for a length of time sufficient to obtain a reasonable depth of case. These heats may be said, in a general way, to correspond with temperatures of about 100° F. over the upper critical range of the steel to be carburized. Although the depth of case is largely dependent upon the temperature, as well as upon the time of carburization, under the above conditions it should be considered poor practice to raise the temperature to the high limit simply for the purpose of reducing the time element; the repair items on the furnace will increase, the fuel cost will be greater, and—above all—the maximum carbon concentration and the relation of the various zones to each other so changed that the whole character of the finished product may be altered.

**Relation of Temperature to Grain-Size.**—Another important feature in determining whether or not to use a high temperature for case carburizing is the relation of such temperature to the grain size. As has been explained in previous chapters, upon passing the  $A_{c1}$  range on heating the grain size begins to coarsen, and most noticeably so after passing the upper critical range or the low carburizing temperatures. Thus from about  $1550^{\circ}$  F. and so on up to  $1850^{\circ}$  or  $1900^{\circ}$  F. (which are about the maximum temperatures used) the grain increases in size most markedly. This increase in grain size has a direct bearing upon the impact strength of the steel, as is shown by the following results (by Guillet) obtained by annealing case-hardening steel bars at the temperatures given for eight hours, and which under the conditions of a normal annealing gave an impact test of 28 kilogram-meters.

Temperature, ° F.	Impact Test, Kilogram-metres.
1470	26
1560	28
1650	15
1740	12
1830	4
1920	3
2010	4

Thus it will be seen that any heating of long duration at temperatures above the upper critical range (the low case carburizing temperature) greatly lowers the resistance of the steel to impact or shock. When high temperature carburizing is necessary, however, suitable treatment after carburizing may be used to "regenerate" the core. Even then, however, the effect of long-continued heating at high temperatures is often manifest.

**High-temperature Carburization.**—Although the advisability of using the lower temperatures for case carburizing has been emphasized, it must not be thought that the higher temperatures of  $1800^{\circ}$  F., or even higher, are never to be used. Contrarily, the latter are often mandatory in certain classes of work where speed of penetration is the first requisite, or where low cost of production is necessitated and the absence of brittleness is not a prime factor. If overheating and burning are suitably guarded against, and the methods of packing are such as will keep warping and distortion at a minimum, and the carburizing process is followed by a technically

adjusted series of heat treatment operations, most excellent results can be obtained. In fact, it is only within comparatively recent years that the use of the lower temperatures has been practiced to any great extent; a decade or so ago if 1550° F. or thereabouts had been suggested as giving greater efficiency, the proposal would have been laughed at by the majority of "practical" hardeners.

#### COMMERCIAL DATA

**Simple Solid Cements.**—In the foregoing sections we have attempted to give in brief the underlying *principles* which govern all processes of partial carburization. By the use of these principles we have further shown that, in carburizations with gaseous or certain mixed cements, it is possible to so select the conditions of carburization as to obtain with certainty cemented zones of predetermined and definite form. Similarly, the same principles are applicable to carburization with solid cements, although (as we have shown) it is not possible to even approximate the same accuracy on account of the lack of control of such cementations. Nevertheless, a study of the preceding pages should convince one of the importance of using carburizing compounds, the composition and manner of acting of which are definitely known. With such principles and ideas in mind, *it should be comparatively easy for each one to prepare for himself those cements which are much more simple, effective, and of less cost than many of those purchased from dealers at high prices, under fancy names, and of unknown composition.* With these thoughts in mind, we will briefly discuss some of the more simple compounds used in commercial work.

**Wood Charcoal.**—Finely divided carbon is the simplest of the solid cements, the purest form in commercial practice being wood charcoal. As we have seen, the carburizing activity of powdered wood charcoal is dependent upon the formation and action of carbon monoxide, and which is further diluted by the nitrogen of the occluded air. It is evident that the use of this charcoal in the ordinary short carburizations for the production of cases of  $\frac{1}{64}$  to  $\frac{1}{32}$  in. in thickness will have the tendency to give cemented zones of low and irregular carbon content. Its use for the deeper carburizations, however, may be distinctly advantageous, as it opposes the formation of zones too high in carbon. Figs. 74 and 75 show the effect of temperature upon carburizations with wood charcoal, the first figure representing carburizing at 1560° F., and the second photomicrograph at 1925° F.



**Animal Charcoal.**—Thus, for thin cases, wood charcoal is generally mixed with certain proportions of the less pure charcoals, such as those produced by the carbonization or charring of leather, bones, hoofs, horns, hair and other animal refuse, etc. In these last cements we therefore have the action of pure carbon or charcoal greatly intensified through the generation of volatile hydrocarbons. We will later mention the influence of the phosphorus and sulphur which these cements may contain. By mixing wood

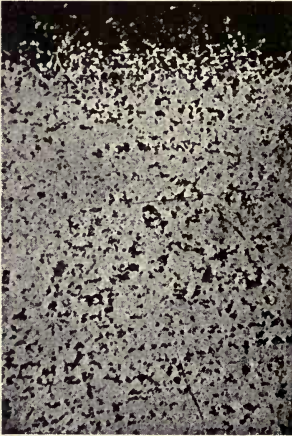


FIG. 74.—Carburization with Charcoal for One Hour at 1560°F., 0.11 per cent. Carbon Steel. (Nolly and Veyret.)



FIG. 75.—Carburization with Charcoal for One Hour at 1925°F., 0.11 per cent. Carbon Steel. (Nolly and Veyret.)

charcoal with definite proportions of these animal charcoals, the carburizing action may be roughly adjusted between the minimum value to be obtained with wood charcoal and the maximum value of the animal charcoals. Of the more common “mild” cements thus obtained we may mention the following:

	Parts
a. Powdered oak charcoal.....	5
Powdered leather charcoal.....	2
Lampblack .....	3
b. Wood charcoal.....	7
Animal charcoal.....	3

	Parts
c. Powdered beech charcoal.....	3
Powdered horn charcoal.....	2
Powdered animal charcoal.....	2

**Common Salt.**—Common salt (sodium chloride) is used in many works in addition to charcoal, it seeming to give better results than wood charcoal alone. Exactly what is its specific action is not thoroughly understood. Thus we have the mixture:

	Parts
Wood charcoal.....	7 to 9
Common salt.....	3 to 1

**Barium Carbonate.**—One of the best solid cements for general use is that consisting of:

	Parts
Barium carbonate.....	40
Powdered wood charcoal.....	60

Its action is well known and is as we have previously described. For cases of small depths it gives carburized zones markedly more homogeneous than those furnished by other solid cements. Giolitti sums up its advantages as follows: "In general, the maximum concentration of the carbon in the cemented zones obtained with carbon and barium carbonate at temperatures between 1650° and 2010° F. varies from a minimum of about 0.7 per cent., for the very thin zones obtained near 1650°, to a maximum of about 1.3 per cent. for the zones thicker than 1 mm. (0.04 in.) obtained near 2010° F.

"Another advantage of this cement lies in its property of being 'regenerated' easily and spontaneously when it is left exposed in a thin layer to the air, after having been used in the usual manner. This process of regeneration is due to the fact that the barium oxide formed during cementation by the dissociation of the barium carbonate, absorbs carbon dioxide from the air, again forming barium carbonate. After a certain number of alternating cementations and regenerations it is necessary to add some wood charcoal to the cement to replace that burned during the cementation and during the discharging of the boxes.

"The preparation of this cement consists simply in finely grinding and intimately mixing the wood charcoal and barium carbonate. If the natural barium carbonate (witherite) is used, it is necessary to powder it carefully before adding it to the carbon; the finely

divided precipitated barium carbonate, on the contrary, can be mixed directly with the granulated carbon and the one operation of grinding the carbon can be used for preparing the mixture."

It is, of course, not always necessary to use the above mixture ratio of 40-60, although this combination has been shown to give about as good results as may be obtained. The conditions of heating, temperature, size of the pieces, type of carburization box and method of packing, etc., will alter each individual carburization, and experiments should be made to determine as exactly as possible the proper combination of the different factors of carburization which

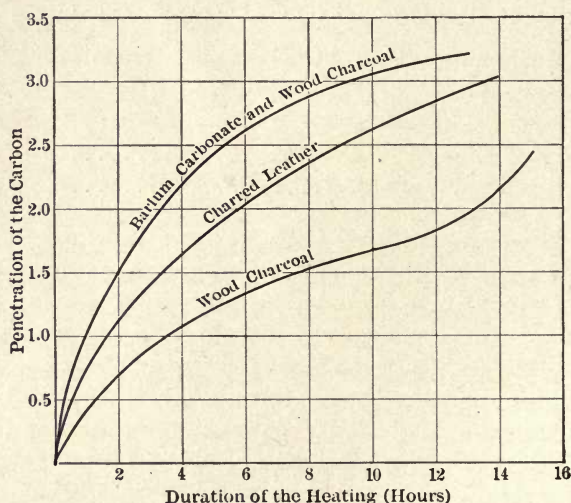


FIG. 76.—Carburization with Common Carburizing Compounds. (Scott.)

enter into consideration. One of the governing factors which is often overlooked is the action of the charcoal, dependent upon its composition. Thus much of the ordinary commercial charcoal still contains considerable volatile or organic matter (hydrocarbons) which may distinctly alter the effect of the carburizing. In order to reduce the intensifying action of such constituents, and to reduce the formation of the hyper-eutectoid zone, it is always advisable first to calcine the charcoal before using.

The general relation existing between the depth of penetration due to charcoal, charred leather, and the usual 40-60 barium carbonate-charcoal mixture is graphically shown in Fig. 76, obtained by Scott in the carburization of soft steel bars at 1650° F.



**Gradual Cements.**—The cements which we have just enumerated are generally classed as “gradual,” for reasons previously given. Yet on the other hand, these same cements, under different conditions of carrying out the carburization, act as “sudden” or “quick” cements. Thus the barium carbonate mixture when used at low temperatures, or for the carburization of pieces of large dimension which heat up slowly, may furnish cemented zones in which the maximum carbon concentration may not be over the eutectoid ratio (0.9 per cent.). The same mixture, on the contrary, may become a sudden cement at the very high temperatures and in carburizing objects of small dimensions.

**Other Solid Cements.**—In addition to the use of charcoal plus the animal charcoals, barium carbonate and common salt, the other agents which may be added are innumerable. To give a list of them would occupy several pages, besides leading to the inevitable conclusion that the efficacy of the majority of them is small, or might be even detrimental. For it should be stated with emphasis that the more simply and more chemically definite a cement can be made, the greater will be the industrial advantages.

**Sudden Cements.**—The nature of the most important of these additions is to make the mixture act quickly, giving rise to a thin cemented zone of high carbon in a very short interval. Thus we have the use of coke saturated with mineral oil, of the saturation of the charcoal in solutions of cyanides or ferrocyanides, and of the presence in greater or less quantities of the concentrated salts of cyanogen as specific additions. Of those used in practice, the following example is extremely interesting:

11 lbs. prussiate of potash,  
 30 lbs. sal soda,  
 20 lbs. coarse salt,  
 6 bushels powdered hickory charcoal,  
 30 quarts water.

Grenet recommends the following cements which have given good results in practice:

	Parts.
a. Powdered wood charcoal.....	1
Salt.....	$\frac{1}{2}$
Sawdust.....	$1\frac{1}{2}$

	Parts
b. Coal with 30 per cent. volatile matter.....	5
Charred leather.....	5
Salt.....	1
Sawdust.....	15
c. Charred leather.....	10
Yellow prussiate.....	2
Sawdust.....	10

The velocity of carburization increases gradually from the first to the third of these cements. The sawdust, by making the mass more porous, increases the activity of the gases.

**Size of the Carburizing Box.**—The selection or general design of the box or container for carburizing is worthy of more attention than is frequently given to it. In the attempt to get a uniform case, much thought and research has been given to the selection of the steel, the carburizing mixture and the degree and duration of heating; and yet in many instances it has all proven unavailing. It must be remembered that the inside of a small box takes quite a while to come up to the temperature of the furnace; and that if a large box is used, the material in the center may, and does, lag behind the indicated furnace temperature several hours or its time equivalent—several hundred degrees. The greater the size of the box, the larger will be this error, and the greater the actual difference in the thickness of case taken on by steel near the sides of the box as compared with that near the center of the box. No manipulation of the furnace can change this effect; it can only be remedied by altering the dimensions of the box itself. Here, then, lies one explanation of many unexplained failures.

The box should not be larger than is absolutely necessary, even where large quantities are to be carburized in it. It should be narrow in at least one dimension so that the heat has a chance to penetrate quickly at least from two sides and reach all the contents at about the same time. Further, the boxes should not be made too deep in proportion to their other dimensions, as it makes it more difficult to pack the parts into them if so made. Whenever possible, the design of the box should follow the outline of the piece to be carburized, allowing about 1 to 2 ins. all around for clearance and packing, so that the surfaces may be uniformly heated and carburized alike.

**Material for Boxes.**—Malleable iron probably gives as good satisfaction as any of the materials used in making the boxes. Cast-



iron boxes, although of comparatively small initial cost, will not stand reheating very many times, and have the further objectionable feature of being somewhat porous. Soft-steel plates and wrought iron may also be made up into good boxes.

The thickness of the wall forms an important feature of the box, for if it is too thin it easily burns through, and if too thick it offers too much resistance to the penetration of the heat to the interior. For the ordinary size boxes, wall thicknesses of  $\frac{1}{8}$  to  $\frac{1}{4}$  in. are common practice. The boxes should be provided with feet so that the heat may circulate all around them. The cover should be as close fitting as is practicable, and should also be provided with ribs along the top to prevent excessive warping. Ribs along the side also add to the service of the box, besides making handling with grappling irons more easy. The sides of the boxes should taper slightly towards the bottom so that the contents can be the more quickly dumped out.

**Packing.**—Carefulness in packing is fundamental to good practice and uniformity of results, just as much as carefulness in heating or treatment. The method of packing should be such as will insure as nearly as possible the even heating and uniform carburizing of all pieces in the same box.

The method of packing must necessarily vary with each type of article to be handled. Heavy pieces, or pieces of regular shape, do not require the care and patience which should be used with pieces of intricate design or with those which on account of their size and shape may be readily influenced by high temperatures. The packing of such pieces must be individualized. For example, long, slender pieces should always be packed vertically, so that the pieces will be held in position by the carburizing material and cannot sag under the influence of the high temperatures. Again, gears and similar pieces may be most suitably packed in tubes, so that the same amount of carburizing material and the same degree and length of heating may influence all parts of the periphery in equal proportion. In carburizing screws and bolts it is well to distribute them in the box in two opposite rows, each row having the head of the screw towards the side of the box and the stem towards the center. New compound may be used at the sides and old compound in the center. Owing to the difference in heat and the difference in the carburizing power of the compounds, this will cause a much deeper carburization of the heads than of the stems—which is exactly what is desired. Again, should a narrow or low box not be available in connection with small work, carburizing compound which has been used once



before may be put next to the sides of the box while the new compound is placed in the center. In this way the difference in carburizing which might result from the different temperatures in various parts of the box may be offset.

The first step in the general operation of packing is to cover the bottom of the box with the compound to a depth of  $1\frac{1}{2}$  to 2 ins., tamping it solidly into place. The parts to be carburized are then placed firmly upon this bed so that the compound and work are in close contact with each other. The pieces should in no case touch the sides of the box, but should be placed about 1 to  $1\frac{1}{2}$  ins. away from it. Further, the articles should be separated from each other by at least  $\frac{1}{2}$  to 1 in., dependent upon their size and the depth of case desired. If the articles should touch one another, it is evident that the carburizing action will have less influence at that particular point—with resulting soft spots. Non-uniformity of case may also result if there is not sufficient carburizing material in the box; it is better to err by using too much than too little.

After the first layer of work has been placed in the box, it is entirely covered with the carburizing compound. This should be packed and tamped down around and over the pieces so as to have the particles of cement in close contact with the steel, but yet not so tightly as to prevent the free circulation of the carburizing gases which are generated during the heating process. When the first layer has thus been suitably packed and covered, the same procedure is repeated until the box is nearly filled. The point to be kept in mind is that each and every piece should be surrounded on all sides by a suitable amount of the carburizing compound.

At least 2 ins. of the compound should form the top blanket over the last layer of work. Some shops adopt the following, with the aim of further preventing the escape of the gases: about 2 ins. from the top of the box sheet-steel strips about  $\frac{1}{16}$  in. thick are laid over the last layer of the carburizing material and these, in turn, are covered with about 1 in. of powdered charcoal. When the box is finally packed, the cover is placed on the box and the edges are carefully sealed with fire-clay or asbestos cement. The box is now ready for the heating operation.

**Type of Furnace.**—It is not our intention to recommend any particular type of furnace for carburizing work, but rather to emphasize the necessity of designing the furnace to suit the work. And, as is evident, the conditions will vary greatly from one plant to another.

There are three main points which should be taken into account for case-hardening furnaces. (1) The furnace shall be capable of attaining easily the maximum temperature which shall be necessary for the carburizing work, and which temperature may be as high as 2000° F. (2) It must be possible to obtain a thoroughly uniform heat application at any of the intervening temperatures, and of maintaining that uniform heating with little or no variation hour after hour. (The effect of oscillating temperatures has been described.) (3) The atmosphere in the furnace shall be non-oxidizing, in order to protect the carburizing boxes from the intense oxidation which would otherwise occur at the high temperatures necessary.

**The Heating.**—The two principal points to be mentioned under this heading are: the heating, at least up to 1300° F., should be gradual; (2) the heating beyond this temperature should be uniform over all parts of the carburizing box. It has been shown by several experimenters that the energetic liberation of gases commences very strongly at temperatures somewhat under 1300° F. for the majority of solid cements, and it is advisable to diminish this factor as much as possible in order to obtain a more gradual cementation. Furthermore, it gives more opportunity for the steel to adjust itself to the effect of heating. The second point made is self-evident: non-uniformity of heating must necessarily result in non-uniformity of product.

**Sulphur Diffusion.**—The influence of sulphur contained in the cements is an extremely important factor in carburization carried on with solid cements. Grayson<sup>1</sup> has produced uncontrovertible evidence that sulphur will diffuse into iron at the temperatures ordinarily used for carburization with such substances as charred leather (which, under the conditions of his case-hardening experiments, contained 0.55 per cent. total sulphur), and that this sulphur combines with the manganese and iron to form manganese and iron sulphides.

Thus in Fig. 77, which is a photomicrograph of a piece of 0.17 per cent. carbon steel carburized for six hours at 1650° to 1750° F. with charred leather, it will be noticed that on the edge are present, in large quantities, sulphide of manganese, also sulphide of iron with ferrite crystals intermingled. That this is sulphide was later proven by means of silver prints and by analysis—which showed 2.10 per cent. of sulphur increase in the first 0.0025 inch.

<sup>1</sup>S. A. Grayson, Inst. Journ., No. 1, 1910.



This sulphur diffusion is a very serious matter, because when the surface is saturated, as in this figure, it tends to produce a soft skin,



FIG. 77.—Soft Case Due to Sulphur Diffusion. (Grayson.)



FIG. 78.—Sulphides Diffusing Further into Case with Higher Temperatures of Carburization. (Grayson.)



FIG. 79.—Sulphide Globules in Carburized Steel after Hardening. (Grayson.)

and even if present in smaller proportions it will weaken the structure considerably, thus making it very “chippy,” consequently causing



two effects which must essentially be avoided in any case-hardened work.

In Fig. 78, being a similar steel carburized at  $1750^{\circ}$  to  $1830^{\circ}$  F., the sulphide is again present, but not in such a large proportion; thus the higher temperature has volatilized still more of the sul-

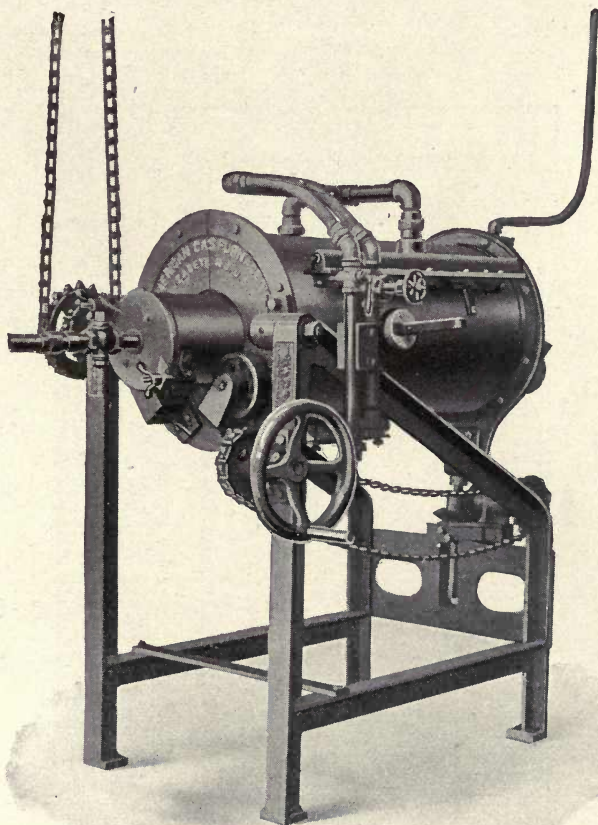


FIG. 80.—American Gas Furnace Co.'s Carburizing Machine.

phur from the carburizing material. Fig. 79 shows the same carburized piece as in Fig. 77, but afterwards reheated and quenched in water from  $1380^{\circ}$  F. In this reheating the sulphide tends to "ball" itself up, and, if anything, diffuse further in.

Thus it may be seen that, for proper carburizing, the solid cements should be as free from sulphur as is possible. On the other

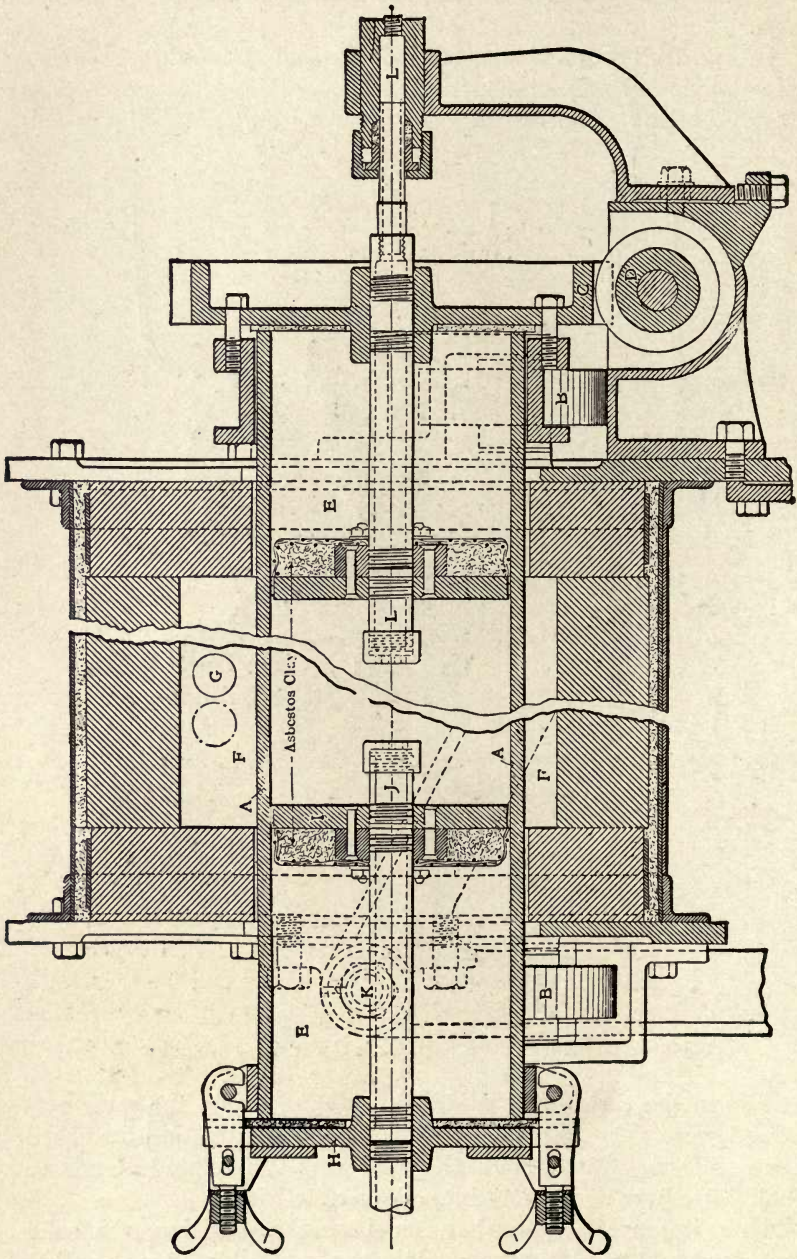


FIG. 81.—Sectional View of Carburizing Machine. (American Gas Furnace Co.)



hand, the barium carbonate mixtures generally used do not contain sulphur, and this sulphur diffusion cannot take place.

**American Gas Furnace Process.**—The apparatus for carburizing

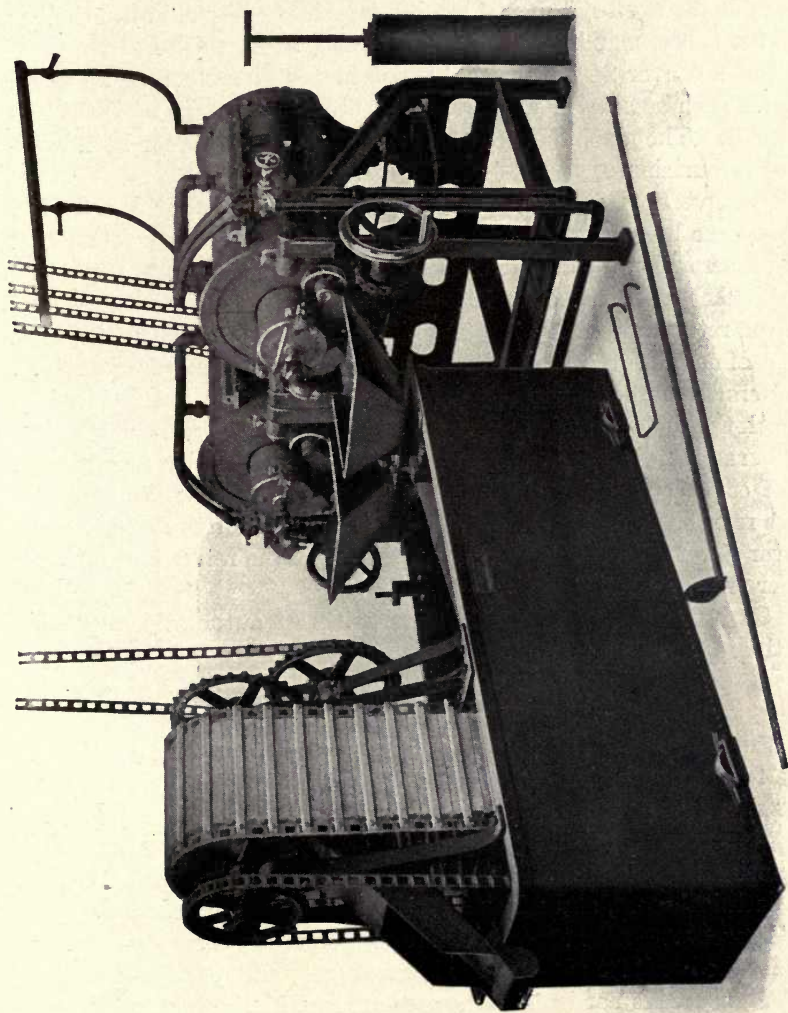


FIG. 82.—Carburizing Machines Connected with Automatic Quenching Bath. (American Gas Furnace Co.)

with gas, as devised by the American Gas Furnace Company, is shown in Fig. 80. The carburizing machine consists of a carburizing retort enclosed by a cylindrical furnace body in which it rotates,



together with suitable arrangements for charging and discharging the work, burners for securing a proper distribution of the fuel, and supply pipes for gas and air. The machine shown has a space available for work of 30 ins. in length by 7 ins. in diameter. It is suitable for work not over 6 ins. in diameter or 20 ins. in length; for shafts, tubes, mandrels and bars of nearly equal thickness throughout of not over 24 ins. in length or 5 ins. in diameter; or for small pieces such as screws, washers, discs, etc., of a charge of about 100 pounds. The machine uses ordinary illuminating gas for both heat- and carburizing.

The vertical section, Fig. 81, through the center lengthwise, shows the heavy wrought-iron retort *A*, which is slowly rotated on the rollers *BB* by the gear *C*, in contact with worm *D*, propelled by a sprocket and chain belt. The reference letters *EE* show air spaces in the retort formed by the two pistons *I*, between which the work is confined, to the properly heated central section of the retort. Letters *FF* indicate the heating space surrounding the retort, into which the fuel gas and air are injected under pressure, from two rows of burners indicated in the upper half of the casing by the letter *G*. The cover *H*, closing the retort, is connected with the piston-like disc marked *I*, by the pipe *J*, which is the vent of the retort. The cover *H* and disc *I* are withdrawn to charge the retort and replaced after the work is inserted.

Carburizing machines connected with an automatic quenching bath are shown in Fig. 82.

#### SUPERFICIAL HARDENING

Superficial hardening differs from case carburizing in that in the former method the outer and higher carbon section constitutes a "skin" of only a few thousandths of an inch in thickness, while in the case-carburizing process the carburized zone forms a case of noticeable thickness. Exactly the same principles apply, however, in both instances, and which have been previously explained.

**Processes.**—The superficial hardening processes may be grouped under the headings of "cyanide hardening" and "pack hardening."

The cyanide hardening processes are essentially used for the purpose of obtaining an extreme degree of surface hardness (wear) on low-carbon or machinery steel, and in which it is not necessary to obtain high resistance to shock, etc.

On the other hand, pack hardening is essentially a method of heating used particularly for fine threaded tools and other tool-

steel work. The process, when correctly carried out, permits of uniform heating with the entire elimination of oxidation by surrounding the steel with a carbonaceous packing. But further, by prolonging the duration of heating at the hardening temperature, a very thin skin of higher carbon content may be formed, so that pack hardening may develop, either intentionally or otherwise, into a superficial hardening process.

**Cyanide Hardening.**—In cyanide hardening the superficial carburizing and hardening may be effected by one of two general methods: (1) immersion of the object in a bath of liquid potassium cyanide or other mixture with cyanogen as the base, followed by quenching; (2) coating or sprinkling the surface of the object with an adhesive mixture of finely pulverized carburizing cyanogenous salt or "varnish," heating the steel to the proper hardening temperature—and thus melting the cyanide—and hardening as usual. The first or "immersion" process is by far the most efficient, both as to uniformity of the carburized zone and simplicity and uniformity of operation. Further, this first method has the tendency to reduce deformation and oxidation during heating and quenching, since, as previously explained, heating in any molten bath has this effect.

**The Immersion Method.**—The method of cyanide hardening by immersion is quite simple. The salt, usually potassium cyanide (KCN), is melted in a suitable pot-furnace, and is maintained at a temperature a little over the upper critical range of the steel to be carburized and hardened. This temperature, for ordinary machinery steel, is about 1550° to 1600° F. The steel is then immersed in the molten cyanide and kept there until it has been uniformly heated; or this heating may be somewhat prolonged in order to obtain a greater depth of skin. In general, however, it is not advisable to heat for a length of time much greater than ten or fifteen minutes, or at temperatures much over the critical range, since such heating will tend to give non-uniform and high-carbon zones which, after quenching, are intensely brittle and may chip off in service. Quenching is usually done in lime water in order to neutralize the cyanide remaining on the steel. Some concerns adopt the method of immersing the steel in the cyanide as soon as it has become molten, permitting the steel to heat up with the bath, and then quenching as soon as the desired temperature of say 1550° to 1575° F. has been attained.

*It is absolutely necessary to remember that cyanogen compounds are deadly poisonous, and every precaution should be adopted when*



using them. Furnaces should be supplied with hoods which have strong draft. Gloves should be used in handling all work, for if cyanide gets into a fresh cut or scratch it will prove deadly. In some cases, when working at the furnaces, it is even advisable to use face masks and to cover up any exposed parts of the body.

**Cyanide Hardening Plant.**—A battery of twenty cyanide furnaces is shown in Figs. 83 and 84.<sup>1</sup> In front of the first pair of

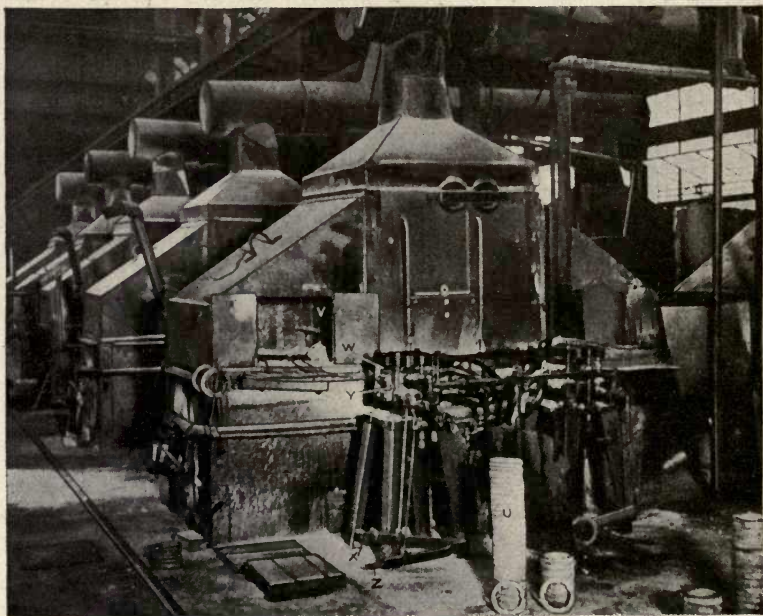


FIG. 83.—Battery of Cyanide Furnaces—Special Quenching Machines for Clutch Rings in Foreground. ("Machinery.")

furnaces in Fig. 83 two special machines are shown which suddenly cool or quench the work as fast as it can be heated and removed from the furnace. They are used for hardening the steel ring discs shown at U. These alternate with brass discs in a multiple-disc clutch on the engine of an automobile. Each pair of furnaces shown in these two figures is covered with a hood to convey the poisonous fumes to the outer atmosphere through pipes extending through the roof. In addition to this, sheet-metal shields are located in front of

<sup>1</sup> E. F. Lake, in "Machinery," Sept., 1914.



the furnace openings shown at V to carry away from the workmen any fumes that might come through these openings. (These shields were removed for photographing.) At the end of the cyanide fur-

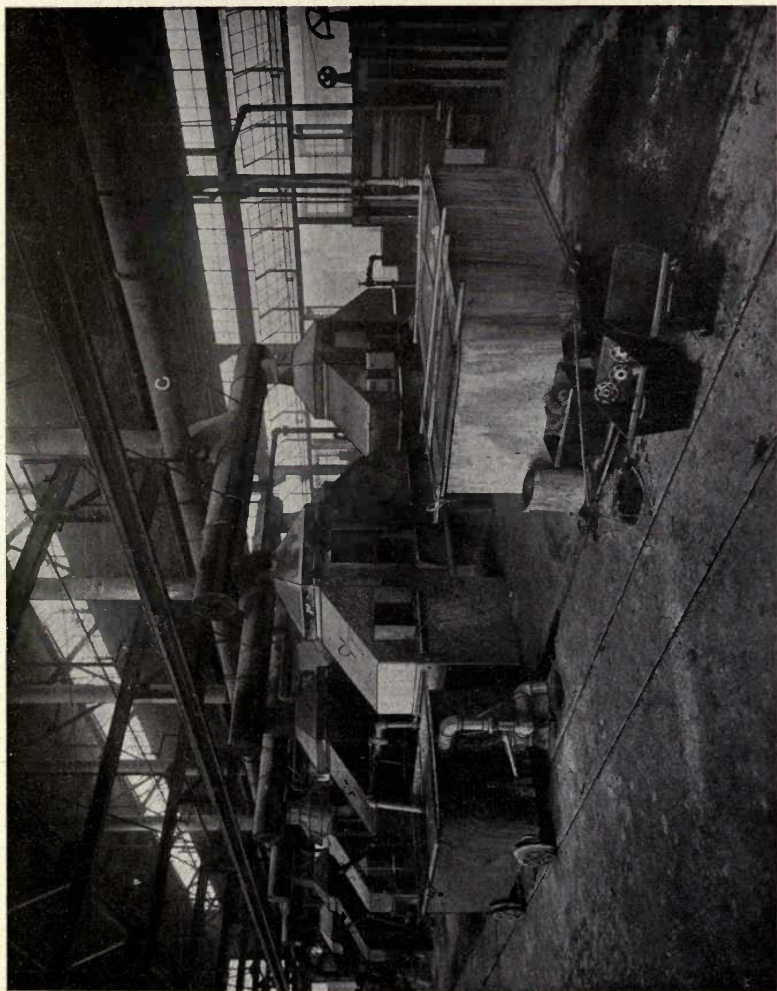


Fig. 84.—Cyanide Furnace, Quenching Tank and Car Tank with Flowing Oil. ("Machinery.")

naces shown in Fig. 84 is a stationary tank of lime water in which some of the work is quenched. On the floor is shown a tray loaded with bevel differential gears and having a long rod for a handle. This is lowered into the cyanide bath to heat the gears, then lifted out and

lowered into the quenching tank, and when cool the gears are dumped into boxes to take to the tempering furnaces. Other parts that are being hardened are shown in the metal boxes beside the tray of gears.

**Other Cyanide Methods.**—The second general process of cyanide hardening, in its simplest form, is to heat the steel to about 1550° F. or so; sprinkle upon it, or plunge it into, potassium cyanide or potassium ferrocyanide; again heat to 1550° to 1600° F. until the cyanide is melted; and then quench in water. In case the amount of cyanide obtained the first time is insufficient, the operation previous to quenching may be repeated until a layer of the required thickness is obtained. It is, of course, necessary to have a clean surface, free from scale and oxidation, so that the carburizing reactions may take place readily.

Other more elaborate processes based upon the above are in use, and involve the application of special carburizing varnishes. On the whole, however, the simpler the process or carburizing compound, the more efficacious will it be in actual and everyday practice.

**Pack Hardening.**—Pack hardening, as a superficial carburizing process, so raises the carbon content in the surface of the steel that the tools may be hardened in oil—instead of in water—and still obtain the requisite degree of either cutting or wearing hardness. For certain work requiring almost perfect hardening results this method cannot be overestimated. In cases in which the required degree of hardness may usually be obtained only by the use of water quenching, oil quenching may now be used; and with it will be associated the toughness of core inherent with the use of oil as a quenching medium. Further, on account of the uniformity in heating and the use of oil quenching, the tendency to crack or warp is largely eliminated.

The method is, in fact, a case-carburizing process. The packing in boxes is carried out in exactly the same manner as is carburization with solid cements, and similar precautions should be used to prevent the tools being jarred out of position or touching each other. In pack hardening, however, to each tool or piece of steel should be attached a wire, so that the tool may be removed promptly to the quenching bath when the requisite degree and duration of heat has been attained.

The temperature to be used should be but slightly over the critical range of the steel, thus differing from the higher temperatures which are customary in case-carburizing processes. As the pack-hardening process is usually used for steels of tool-steel analysis,

this temperature will be about 1375° to 1400° F. The length of time required for the heating will, of course, depend upon the size and number of the pieces to be treated in one box, and the depth of skin desired; for ordinary small tools this will generally be about two hours after the proper temperature has been attained by the steel itself.

Packing material which would be harmful to the steel should not be used. Bone, for example, usually contains phosphorus, which is apt to make the steel brittle—although burnt bone is not as high in this element as is raw bone. Sulphur must also be guarded against. If the initial steel does not contain more than 1.20 or 1.25 per cent. carbon, charred leather makes a very good packing material. If the carbon content exceeds these values, charred hoofs, or a mixture of charred hoofs and horns is better than charred leather, since the latter will under such conditions have the tendency to give a too highly carburized and brittle zone.

The temperature of the steel in the box may be gauged by means of test rods the same size as the tools, or by test wires, or by suitable pyrometer equipment.



## CHAPTER VII

### CASE HARDENING: THERMAL TREATMENT

**Heat-treatment Requirements.**—It may be said that practically all objects which have undergone the case-carburizing processes previously described require a subsequent heat treatment of some nature. As one of the essential aims of the case-hardening process is to produce a hard-wearing surface, and as carburized steels through their slow cooling from high temperatures will be more or less lacking in this necessary hardness, it is evident that a hardening process is necessary. In dealing with the subject of case hardening we will therefore assume that the carburized steel must undergo some hardening process or processes which will bring about this desired condition of affairs.

Secondly, in order that we may at once differentiate the ultimate aims of such hardening, and simplify our discussion, we will assume that we also desire to obtain a minimum brittleness in both case and core. Previous explanations prove that this condition requires that the "grain size" be reduced to a minimum, that is, that the steel as a whole must be *refined*.

To sum up, the specific aims which we have in view require that the heat treatment shall combine hardening and grain refinement.

**Comparison with Homogeneous Steels.**—The heat treatment of a carburized steel differs from that of a homogeneous steel only in the fact that, instead of considering the influence of such treatment upon *one* steel, we really have to do with two, or even three main classes of steels at once. That is, the carburized steel consists of (1) the core, or low-carbon steel; (2) the carburized zones of the case with about 0.9 per cent. carbon as the maximum; and, in many instances, (3) the carburized zones of the case which, under conditions of slow cooling from the temperature of carburization, contain an excess of free cementite, i.e., greater than 0.9 per cent. carbon. Our heat treatment must therefore be adjusted so as to superimpose the effect of one class upon the other.

Now as the present tendency of case carburizing in industrial practice is to preclude the formation of zones containing free cement-

ite (class 3), we will postpone the discussion of the heat treatment which involves that class, and thus further simplify matters. We now, therefore, have but to consider the related heat treatment of steels of very low-carbon content and those containing the eutectoid ratio of carbon as a maximum.

**Effect of the Temperature of Carburization.**—Into this heat treatment there now enters the factor of the temperature of carburization, and its specific influence upon the size of grain in the two classes of steels. In the first place, it is axiomatic that the effect of any heating at, or slightly above, the  $Ac_3$  range for the soft steels, and the  $Ac_{1.2.3}$  range for the hard steels, is to produce the maximum grain refinement (unless such heating is extremely prolonged). And further, that the effect of any heating at temperatures considerably above these temperatures is to produce a size of grain of proportionally greater size for the respective steels. (In this chapter we are using the phrase "grain size" in its general colloquial meaning.) Thus, if carburization were carried out at  $1600^{\circ}$  F. for a case carburizing steel of 0.15 per cent. carbon—that is, at a temperature but slightly over that of the upper critical range of the initial steel—it would produce the minimum grain size in the steel of the core, and a certain and proportionally greater grain size in the steel of the case. Steels carburized at the lower temperatures we will call Group A. Steels carburized at the higher temperatures or about  $1800^{\circ}$  F.—that is, considerably over that of the upper critical range—we will call Group B, the grain size of both core and case being proportionally greater than the minimum.

**Classification.**—We now have a further means of classifying our heat-treatment processes according to the temperature which was used in carburization because of the effect of such temperatures on the refinement of the steel. That is, with carburizations of Group A, the steel of the core will already be refined, and we need only consider the refining of the case; while in Group B the steel of both core and case will require refinement. Both groups will, of course, require the hardening of the case.

**Treatment of Group A.**—Assuming the conditions as in Group A (carburization at a temperature slightly over the upper critical range of the initial steel), it is evident that the complete heat treatment following carburizing will only require the hardening and refining of the case, in which, by previous assumption, the maximum carbon content is about 0.9 per cent. A consideration of the principles of heat treatment at once shows us that a single quenching at about

1375° F., that is, slightly over the A1.2.3 range, will bring about the fulfillment of both of these conditions. Further, the quenching at this temperature, and under existing conditions, will not affect the present refinement of the core, nor—if the carbon content is low—will it increase the brittleness due to the changing of the pearlite of the core into martensite (in fact, it has the opposite effect of increasing the toughness in the very low carbon steels). Thus, by this single quenching, we have completed the requirements originally demanded.

**Treatment of Group B.**—Turning now to case carburizations at the higher temperatures, Group B, it is evident that in addition to the refining and hardening of the case we must also refine or regenerate the core. This, we know, may be best accomplished by quenching the previously cooled steel at a temperature slightly above the A<sub>c3</sub> range of the steel of the core. This quenching will put the entire steel, both case and core, in the martensitic condition, refine the core, but not refine the case. By following this first quenching by the quenching at the lower temperature described in the previous paragraph we accomplish the following: the hardness and refinement of the case reaches a maximum; the refinement of the core produced by the first or regenerative quenching is not changed; the strains or brittleness which may have been produced in the core through the first quenching are relieved. In other words, by superimposing one quenching upon the other we have attained the desired properties.

**Effect of Hyper-Eutectoid Zone.**—The next variable is that due to a hyper-eutectoid zone in the case, or carburized steels which contain free cementite upon slow cooling from the temperature of carburization. If we apply the treatment previously described under Group A the condition of this free cementite will not be affected. This is due to the fact that, upon heating, this free cementite is not dissolved by the solid solution austenite until a temperature corresponding to the A<sub>cm</sub> range (see Fig. 13) of the maximum carbon content of the case is attained, and which is obviously higher than 1375° F.

**Influence of Free Cementite.**—Now it has been repeatedly demonstrated in practice that the presence of free cementite existing, as it usually does, in the form of films between the grains (i.e., as a network), or even as spines, increases the brittleness of the case, interposes lines of weakness, and often results in the chipping off of parts of the case. (Incidentally it might be mentioned that this



is another reason for desiring a maximum carbon content in the case of about 0.9 per cent. when suitably adjusted and controlled methods of heat treatment are not used.) To eliminate this source of danger—the free cementite—it will be necessary to heat the steel above the  $A_{cm}$  range of the steel of the case in order to get this cementite “into solution,” and to then “fix” it in that condition by quenching from that temperature. Now, *provided* that the maximum carbon content is not sufficiently high so as to raise this  $A_{cm}$  range above the  $A_{c3}$  range of the steel of the core, it is apparent that the treatment of Group B previously noted (the double quenching) will also serve in this instance. This treatment will likewise be applicable, with the above proviso, regardless of the temperature of carburization.

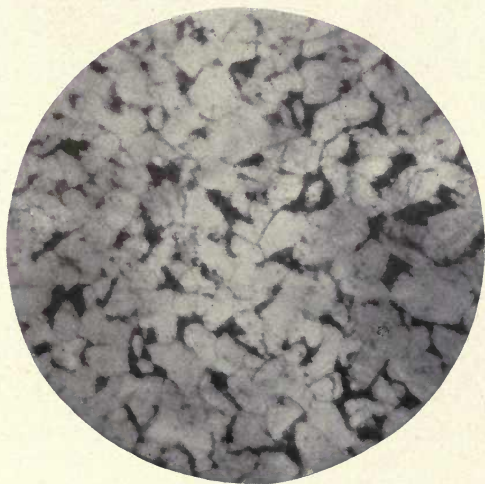


FIG. 85.—Core of Steel Carburized at 1830° F. and Slow Cooled. (Bullens.)

**Photomicrographic Study.**—The principles brought out by this series of treatments and their individual effect on the case and core may be more graphically illustrated by means of the series of photomicrographs shown in Figs. 85 et seq. The steel in these photomicrographs represents an ordinary low-carbon steel which has been cemented at 1830° F. in such a manner as to produce a carburized zone containing greater than 0.9 per cent. carbon. In all cases the steel has been allowed to cool slowly from the temperature of cementation.

**Structure after Slow Cooling.**—The micro-structure of the core upon slow cooling is shown in Fig. 85, it consisting of coarse ferrite

(light) and a small amount of coarse pearlite (dark). Similarly, the micro-structure of the external layers of the case is illustrated in

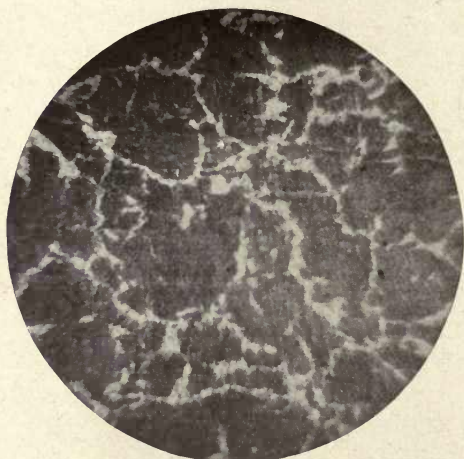


FIG. 86.—Case of Steel Carburized at 1830° F., and Slow Cooled. (Bullens.)

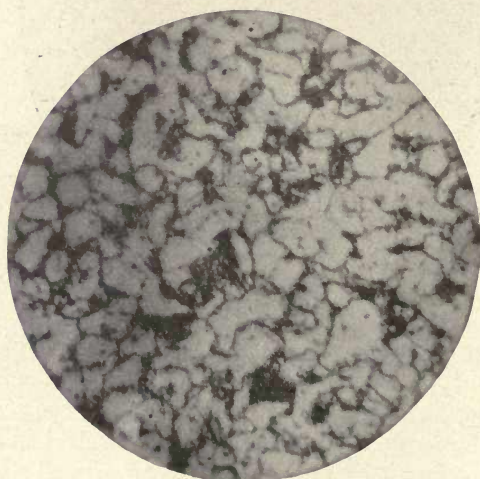


FIG. 87.—Core of Steel Carburized at 1830° F., Slow Cooled, and Quenched from 1375° F. (Bullens.)

Fig. 86, in which it is seen that the large grains of sorbitic pearlite are surrounded by the characteristic network structure of free cementite. In other words, the steel as a whole exhibits the non-

refinement characteristic of the high temperature of carburization, and the case is further weakened by the presence of free cementite.

**Effect of Lower Quenching on the Core.**—If we should now quench the steel from about 1375° F., we see from Fig. 87 that the effect upon the core is to change the pearlite into martensite plus osmondite (the darker areas), to slightly increase it in amount (on account of the fact that this quenching temperature is somewhat above the A1 range), but does *not* give any great amount of grain refinement to the core as a whole.



FIG. 88.—Case of Steel Carburized at 1830° F., Slow Cooled, and Quenched from 1375° F. (Bullens.)

**Effect of Lower Quenching on the Case.**—Similarly we see from Fig. 88, representing the micro-structure of the hardened high-carbon case, that, although the initial pearlite itself (compare with Fig. 86) has been refined, as well as changed into hard martensite, the cementite network has remained unaffected. This last consequently causes the original coarse structure of the case as a whole to be retained (that is, unrefined), as well as the inherent brittleness due to this free cementite.

**Regeneration of the Core.**—Now by quenching the steel from a temperature just above the upper critical range of the steel of the



core, or at about 1650° F., we see from Fig. 89 that the core consists entirely of homogeneous martensite, and further, that the former coarse grain has been entirely obliterated. In other words, we have "regenerated" the core.

**Effect of Regenerative Quenching on the Case.**—The effect of this same regenerative quenching upon the high-carbon case is shown in Fig. 90. From this photomicrograph it is evident that, although we have effected a rearrangement and entangling of the cementite (white) and thus largely reduced the weakening and embrittling effect of the free cementite (as in Fig. 86), the

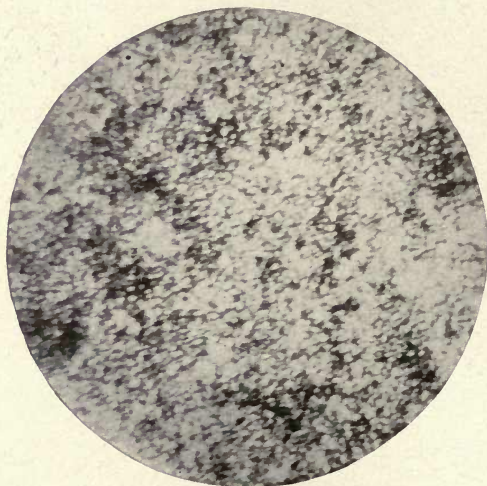


FIG. 89.—Core of Steel Carburized at 1830° F., Slow Cooled, and Quenched from 1650° F. (Bullens.)

heating and quenching temperature of 1650° F. has not been sufficient to dissolve entirely and "fix" the cementite in the martensite. It is at once apparent that in this particular steel we have exceeded the proviso regarding the maximum carbon content which we enunciated in a previous paragraph.

**Treatment of High-carbon Case.**—This leads to a consideration of what method we shall apply when the maximum carbon content of the case exceeds that percentage which will cause the Acm range to be above the Ac3 range of the steel of the core. So in this particular instance we have two procedures open to us: we may either

proceed with the quenching at  $1650^{\circ}\text{F.}$ , obtain the best possible refinement of the core, and accept with as good grace as we can the presence of free cementite in the final case—granting that it is better distributed by this quenching than by the treatment as in Fig. 88; or, we may raise the temperature of the initial quenching to such a temperature as will completely dissolve and fix the excess cementite, even though it does increase the grain size (and, therefore, the brittleness) of the core. In either procedure it will of course be necessary to follow the initial quenching by the hardening quenching. The proposition then comes to the point as to which is the more impor-

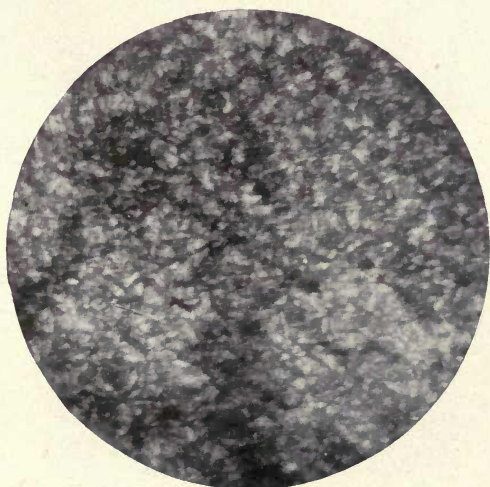


FIG. 90.—Case of Steel Carburized at  $1830^{\circ}\text{F.}$ , Slow Cooled, and Quenched from  $1650^{\circ}\text{F.}$  (Bullens.)

tant, (1) the greatest refinement of the core, or (2) the most advantageous treatment for the case, such as will give minimum brittleness, minimum possibility for enfoliation to occur, and the best wearing surface.

**Effect of Very High Quenching Temperature on the Core.**—Assuming that the higher temperatures, which will be necessary if the second item is to predominate, can be used without the oxidation of the steel (such as by the use of salt baths), excessive warping, and so forth, a study of the photomicrograph of Fig. 91 will aid in solving the problem. This figure represents the structure of the core after quenching at  $1830^{\circ}\text{F.}$ , followed by a second—the “hardening”—

quenching from 1375° F. It is at once manifest that the high quenching heat has not greatly increased the grain size of the core. And further, as the ferrite and sorbite have been distributed over the whole section in fine particles, the core should prove very tough on this account. That is, such treatment will generally prove satisfactory for the core so long as the initial carbon content is not too high, and we may proceed along the lines which shall produce the best case.

**Treatment for "Best Case."**—What, now, is the *best case*—in other words, the best wearing surface; and how may it be obtained? From previous discussion, and from a study of the photomicro-

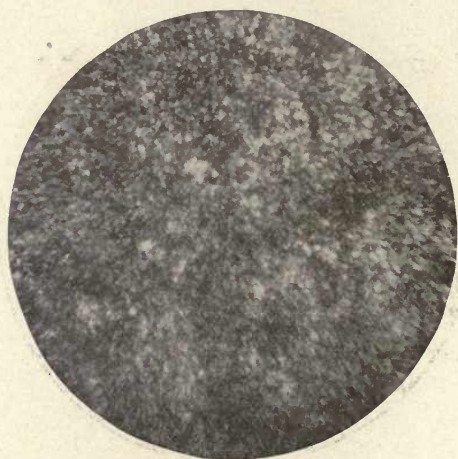


FIG. 91.—Core of Steel Carburized at 1830° F., Slow Cooled, and Double Quenched from 1830° and 1375° F. (Bullens.)

graphs of this and the preceding chapter, it must be evident that the best wearing surface, all things considered, is not characterized by the presence of free cementite as a network or as spines. Granting this, the way by which this condition may be avoided, assuming that the carburized steel contains a hyper-eutectoid zone, is first to eliminate the free cementite by quenching above the Acm range of the case, and to be followed by a treatment—for purposes of grain refinement and hardening of the case—such as will not reproduce the original network condition of the free cementite. Of necessity, for reasons previously given, this second operation must consist of a quenching at about 1375° F. for straight carbon steels.



**Effect of Double Quenching on the High-carbon Case.**—The effect of these two quenching operations is shown in the photomicrograph of Fig. 92. The steel contained about 1.40 per cent. carbon and was quenched from about 1850° F., followed by another quenching at 1375° F. In this instance it will be noted that the free cementite appears as white dots or "spheroids" upon the darker martensitic groundmass, and that there is not the slightest appearance of the originally characteristic network structure of free cementite. If the temperature of the initial quenching has not been sufficiently high so as to dissolve all the original network of free cementite, a structure will be obtained showing both spheroidal and network cementite.

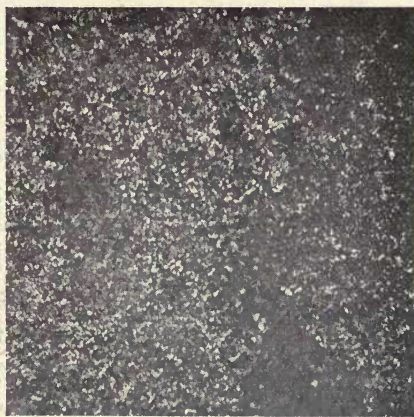


FIG. 92.—1.40 per cent. Carbon Steel, Double Quenched from 1850° and 1375° F.  $\times 60$ .

**Spheroidal Cementite.**—The importance of this spheroidal-cementite type of hyper-eutectoid structure as a wearing surface cannot be over-emphasized. When such a steel is first placed in service, the tendency will be for the martensite gradually to wear away, leaving the extremely hard spheroids of free cementite to take the wear. We then have the ideal conditions for a wearing or bearing surface: the innumerable "points" of cementite, imbedded in the softer and tougher martensite, act as the bearing-points; and this wearing surface may be ideally lubricated through the circulation of oil in the free zone representing the difference between the surface of the cementite and that of the martensite.

**Spheroidal Ferrite.**—This same treatment will effect the “spheroidalizing” of the free ferrite of the hypo-eutectoid zone and of the core in a like manner. In Fig. 93 there is shown the core of a case-hardened steel of 0.22 per cent. carbon which had been double quenched at 1850° and 1375° F. A treatment of this nature will therefore put the whole steel, both case and core, in an analogous condition, and the effect of any “liquation” of either the ferrite or the cementite, caused either by slow cooling or—with cementite—by oscillating temperatures of carburization, will, for the most part, be overcome by such treatment.



FIG. 93.—Core Containing 0.22 per cent. Carbon, Double Quenched from 1850° F. and 1375° F. (Bullens.)

**Avoiding High Quenching Temperatures.**—Referring again to the effect of high quenching temperatures upon the refinement of the core, it may be said that such temperatures will necessarily not bring out the fullest elimination of brittleness in the core. For this, as well as for other practical reasons involved in the obtaining of such high temperatures, it is advisable to avoid their use. This may be accomplished in two ways: by avoiding such carburizing methods as will necessitate their use, as will be evident from the definition which follows; or by a preliminary quenching directly subsequent to carburization which we will discuss a little later.

**Maximum Efficiency in Case-hardened Steels.**—Gathering together some of the facts previously discussed, we will state that the *best wearing surface*, in combination with minimum brittleness of case (as shown by the absence of enfoliation) and of core (as shown by shock tests), as well as with minimum difficulties of treatment, will be had under the following conditions:

(1) When the maximum carbon concentration in the case is greater than 0.9 per cent., but does not exceed that amount which will cause the temperature of the Acm range of the case to exceed the temperature of the A3 range of the steel of the core; and (2) when the following conditions subsequent to case carburizing are rigorously observed and their effect, with the exception of *a*, is at a maximum: (a) Slow cooling from the temperature of carburization (which we will shortly discuss); (b) quenching from a temperature slightly above the A3 range of the initial steel; followed by (c), a quenching from a temperature slightly above the Ac1.2.3 range of the steel.

**Maximum Carbon Content.**—Although the first statement regarding the maximum carbon content which we have recommended, that is, over the eutectoid ratio, is in direct contradiction to the opinion of many metallurgists, it is nevertheless strongly supported by industrial results as well as by theory. But it should also be distinctly noted that the conditions of the specific heat treatments under the second statement are strongly qualified, in that the best technical methods—involving accuracy and uniformity of heating and heat control—shall be instituted, and that the effect of each quenching shall be at a maximum. If such conditions cannot be complied with, it will be decidedly preferable to adopt such methods of carburization as will produce a maximum carbon content in the case of not much exceeding 0.9 per cent.

**Maximum Effect for Cementite Solution.**—For reasons which will shortly be evident, it will be advisable further to amplify the proviso that “the effect of each quenching shall be at a maximum.” First, then, in regard to the effect of the initial quenching upon the solution of the cementite. It is well known that the solution of the free cementite in hyper-eutectoid steels takes place very slowly. Due to this sluggish action, it will often be found that a heating of short duration slightly above the Acm range will not entirely dissolve the excess cementite. And further, that it is often necessary, in order to avoid a prolonged heating at the apparent Acm temperature, to increase this temperature to a considerable extent. Now when the maximum carbon content of the case is such that the



theoretic Ac<sub>m</sub> temperature is considerably below the Ac<sub>3</sub> range of the steel of the core, it is evident that there will be little difficulty in satisfactorily obtaining the full solution of this cementite. But, on the other hand, if the two temperatures named almost coincide, it is manifest that the maximum effect of the initial heating and quenching relative to the solution of the free cementite will not always be obtained unless such heating is prolonged. To increase the duration of this heating is also inadvisable, because this would tend towards the diffusion or equalization of the carbon content in the various external layers; and this, in turn, would be contrary to the purpose for which the high carbon was originally obtained through carburization. Again, quenching from a higher temperature than that originally set would obviously exceed the provisions previously named as those necessary to obtain the best product, and for the present may be eliminated.

**Double Initial Quenching for Solution of Cementite.**—It will therefore be inadvisable to raise the maximum carbon content of the case sufficiently high (through carburization) so as to bring about the condition of affairs which we have just been discussing. If we abide by the arbitrary rules which we have laid down, the only way out of such difficulty, if it should exist, is to *double quench* from the initial temperature.

**Relation of Initial Carbon to Maximum Carbon.**—Another variable which should also be noted under this subject is the influence of the carbon content of the steel of the core upon the Ac<sub>3</sub> range. A study of the chart, Fig. 13, will show that between the minimum carbon content used for case-hardening steels, or about 0.05 per cent., and the maximum carbon, or about 0.25 per cent., there is a difference of about 125° F. This will mean a corresponding difference in the possible initial quenching temperature, and will, in turn, influence the factor of the maximum carbon content in the case which it is possible for us to use under these rules. This factor must therefore be taken into account in the method of carburizing. We may then say that the lower the carbon content of the steel to be carburized, the greater may be the maximum carbon content in the case—again assuming the previous conditions to hold.

**Double Regenerative Quenching.**—Let us now consider the effect of the initial quenching temperature on the core. In the chapter dealing with case carburizing it was stated that the higher the temperature of carburization, and the greater the length of exposure at that temperature, the greater would be the grain size and its

influence upon subsequent regeneration. Under such conditions it will not always be possible to obtain, by a single initial quenching, the full refinement of the core. The only alternative, in order to satisfy the set conditions, will be to *double quench* at the initial temperature.

**Slow Cooling after Carburization.**—In a previous section we mentioned that the first step subsequent to carburization was to allow the steel to cool slowly from the temperature of such carburization. When solid cements are used, the method involving the immediate removal of the cemented pieces from the carburizing boxes and throwing them into the quenching bath cannot be too strongly condemned, especially if there is to be no regenerative quenching. In the first place, it is a practical impossibility to remove all the pieces from the box and to so quench them that the results will be identical. This statement and its logical conclusions hardly need further explanation.

In the second place, in order to obtain a full refinement of the steel, it is absolutely necessary that the material shall be reheated from a temperature below the lowest critical range to a temperature beyond the upper critical range, for otherwise full regeneration will not take place. If the objects have been immediately quenched from a temperature near that of the carburization (i.e., without having been previously slow-cooled), the grain size retained by this quenching will be that characteristic of the highest temperature reached during the carburization. The grain size thus given to the core will be large, because the temperature of carburization must obviously be high if quenching is to take place before the temperature of the steel, during removal from the box, falls below that of the hardening point. If the steel should be put into service in the condition just mentioned, it would not be capable of withstanding any great amount of shock on account of its inherent brittleness. And even if the first haphazard quenching should be followed by a reheating and quenching from slightly above the lowest critical range it is evident from previous discussion that the steel of the core as a whole will not be regenerated.

In other words, if the carburization has given the proper maximum carbon content in the case, previously stated, such a quenching will be of little economic importance because it must always be followed by the double quenching (regenerative and hardening) necessary to produce maximum efficiency. Under such conditions, and for both theoretic and practical reasons, it is advisable to permit the car-



burized steel to cool in the boxes to a temperature at least lower than that of the Ar1 range.

**Benefits from Preliminary Quenching.**—Leaving aside the consideration of those steels which require only a surface hardness, there are only two benefits which can accrue from quenching directly after carburization. First, there is the prevention of the “ liquation ” of the excess cementite during slow cooling, with the possible resulting disadvantages through enfoliation, or similarly, the liquation of the ferrite. The author believes that the effect of this phenomenon of liquation, although strongly emphasized by Giolitti, may be largely counteracted by the results of the *effective* double quenching and its consequent “ spheroidalizing ” action. The use of the preliminary quenching, assuming the proper maximum carbon, may be regarded as of indirect benefit in this first proposition.

Second, and of particular and direct importance, is when the maximum carbon content of the case exceeds that amount at which the temperature of the Ac<sub>m</sub> range is equal to, or greater than, the temperature of the Ac<sub>3</sub> range of the steel of the core. Under these conditions the preliminary quenching—as we call it—will prevent the precipitation and coagulation of the excess cementite into the network and spines which are so difficult to redissolve during regenerative heating. Consequently, this preliminary quenching will permit the direct use of the regenerative quenching at its proper temperature, even though the carbon content of the case is higher than the governing ratio between Ac<sub>m</sub> and Ac<sub>3</sub> and which, under conditions of slow cooling, would demand the use of a higher regenerative quenching. It is manifest, however, that such preliminary quenching, to be effective, must take place at a temperature higher than the specific Ac<sub>m</sub> temperature, or at about that of the cementation proper.

**Use of Salt-bath Heating.**—Before summing up the treatments given in the foregoing pages, there are three points of practical interest which should be noted. The first of these has to do with the method of heating the steel for quenching. It is obvious that oxidation, even of very slight amount, must be entirely prevented. The best and surest method of attaining this is by the use of molten baths. Of these, the salt baths are to be preferred to the use of lead, at least for temperatures over 1500° F., on account of the poisonous fumes of the latter at the high temperatures.

**Interrupted Regenerative Quenching.**—The second item refers to the regenerative quenching. On account of the tendency of the



high-carbon steels to check or crack when high quenching temperatures are used, it is advisable to remove the steel from the water bath when its red color is seen to disappear. As the steel "loses its color" at a temperature under that of the lowest critical range—that is, below that temperature at which the transformation in cooling is totally effected, it is evident that this interrupted cooling will in no wise affect the regeneration of the core. Its influence upon the structure of the case will also have little practical importance, primarily because it is not desired through this quenching to obtain a maximum hardness; and further, because there will be little or no tendency for any excess cementite to precipitate as a network structure. If any of the excess cementite should be thrown out of solution, it is more apt to be of the spheroidal type. Whether or not this cooling is interrupted at about 900° F., it is always advisable to remove the steel from the bath before it has become entirely cold.

**Coagulation of Cementite.**—In the third place, we would refer briefly to the "hardening" or second quenching. If the case contains greater than the eutectoid ratio of carbon, the duration of the heating at this lower temperature should not be prolonged over a greater period than is necessary thoroughly and uniformly to heat the case to the proper hardening temperature. A prolonged heating would have the tendency to coagulate the cementite which is ordinarily precipitated at this temperature, thus opposing the realization of the conditions of maximum effectiveness.

**Summary.**—We may sum up the general situation, and give to each class of steel the treatment which we recommend to obtain the "best wearing surface," combined with minimum brittleness of case and core.

#### *Classification of Case-carburized Steels*

*Group A.* Steels case carburized at temperatures approximating that of the upper critical range of the initial steel.

*Group B:* Steels case carburized at temperatures considerably exceeding that of the upper critical range of the initial steel.

*Class 1.* Maximum carbon content of the case does not exceed 0.9 per cent.

*Class 2.* Maximum carbon content of the case greater than 0.9 per cent., but is less than when  $A_{cm}$  of the case equals  $A_{c3}$  of the core.

*Class 3.* Maximum carbon content of the case greater than that specified under (2).

*Classification of Treatments for Specific Steels*

Group A.	Class 1.	Treatment I.
	2.	II.
	3.	III. or IV.
Group B.	Class 1.	Treatment II.
	2.	II.
	3.	III. or IV.

*Treatment I.*

- a. Cool slowly.
- b. Quench from slightly over the  $Ac_{1.2.3}$ , or about  $1375^{\circ}$  F.

*Treatment II.*

- a. Cool slowly.
- b. Quench from slightly over  $Ac_3$  of the core. Dependent upon the carbon content, this will vary from  $1650^{\circ}$  to about  $1525^{\circ}$  F.
- c. Quench from slightly over  $Ac_{1.2.3}$ , or about  $1375^{\circ}$  F.

*Treatment III.*

- a. Quench directly subsequent to carburization, without slow cooling, from at or near the temperature of carburization but not lower than  $A_{cm}$ . Dependent upon the carbon content of the case,  $A_{cm}$  will vary from about  $1650^{\circ}$  F. for 1.20 per cent. carbon (or thereabouts), to about  $1800^{\circ}$  for 1.45 per cent. carbon. It is not advisable to quench at a temperature higher than  $1800^{\circ}$  F.
- b. Treatment as in II, b and c.

*Treatment IV.*

- a. Cool slowly.
- b. Quench from a temperature over the  $A_{cm}$ , dependent upon the carbon content of the case. (See III, a.)
- c. Quench from slightly over  $Ac_{1.2.3}$ , or about  $1375^{\circ}$  F.

NOTE: This treatment requires a slight sacrifice in the minimum brittleness of core in order to obtain "best wearing surface."

**Mechanical Effects of Treatments.**—The effect upon the mechanical properties of the case and core of various treatments is given in the following table taken from Guillet. The steel used was of the ordinary type for case hardening, classed as "extra soft."

Treatment.	Resistance of the Core to Shock in kg.m.	Surface Hard- ness of the Case, Shore Method.
Non-cemented steel, heated at 1700° F. and cooled in air . . . . .	20.6	
Non-cemented steel, quenched at 1700° F. in water	23.8	
Steel cemented at 1830° F. for 0.047 in. and cooled slowly . . . . .	13.5	38.5
Same cementation; quenched at 1830° F. in water.	23.2	79.8
Same cementation; quenched twice in water, at 1830° and 1375° F. . . . .	25.5	84.0

**Further Treatments not giving Maximum Efficiency.**—Case-hardened objects having a comparatively thin cemented zone ( $\frac{1}{16}$  in. or less) may broadly be divided into those articles which require only surface hardness and work under fairly uniform pressure without shock, and those articles which must withstand shock, bending strains, etc. We have discussed at some length both the carburization and the heat treatment which are required by those of the latter class. The heat treatment of those articles of the first class we have previously referred to, but for purposes of summarizing we may divide it as follows;

#### *Treatment V.*

- a. Quench directly after carburization (without slow cooling), but at a temperature not less than 1350° F., or that of Ar<sub>1</sub>. The results may be varied over a wide range according to the temperature of quenching.

NOTE: This treatment is for those articles which merely demand a hard surface, and in which brittleness and enfoliation may not be considered.

#### *Treatment VI.*

- a. Cool slowly.
- b. Quench from slightly over Ac<sub>3</sub> of the initial steel, varying from 1650° to 1525° according to the carbon.

NOTE: This treatment is for those articles which demand a tough core and a comparatively hard surface—that is, the elimination of brittleness in the core is of more importance than maximum surface hardness.



*Treatment VII.* (Similar to Treatment I.)

a. Cool slowly.

b. Quench from about 1375° F., or slightly over Ac1.

NOTE: This treatment is for articles which demand a maximum surface hardness, or as much as can be obtained from a single quenching, without reference to the brittleness of core or to the dangers of enfoliation through the presence of free cementite. With low temperatures of carburization and with a carbon maximum of 0.9 per cent. this classification would of course correspond to Group A, Class 1.

**Alloy Steels.**—The treatment of alloy steels will be considered under their respective chapters. In the main, however, the theory of treatment does not vary, although the actual temperatures may be changed on account of the influence of certain alloys upon the position of the critical ranges.

## CHAPTER VIII

### HEAT GENERATION

**Distinctive Conditions.**—In industrial heating, and particularly the sequence of operations applied to the heat treatment of steel, it is but hard common sense to state that there is no *general* solution applicable to the heating element or furnace. The application of heat to these various operations, with the accompanying design of furnace equipment, is an *engineering* problem, and it must be considered as such, and in the broadest manner, if the greatest efficiency is to be obtained. No single type of furnace, fuel nor “system” of burning can be applied as a “cure-all.” Each case must be dealt with on its merits and the furnace and the fuel and their application to the work in hand must, in the final analysis, be based upon the results obtained, measured commercially. Consequently, as no two problems are exactly alike, it necessarily follows that the furnace equipment must be designed to suit the individual plant with its distinctive conditions. The average heat-treatment shop needs a drastic awakening from the lethargy of “cut-and-dried” systems, poorly designed and “home-made” furnaces, inefficient treatment and handling of products.

**Quality of Product vs. Cost.**—Quality of product and cost of manufacture are the basis of heat-treating operations. Quality of product covers the proper heating of the material to meet the metallurgical requirements, and its physical condition to meet the mechanical requirements. Cost of manufacture includes the cost of fuel, power, labor, special equipment and material, such as boxes, tools, quenching fluids, etc., as well as fixed charges on the equipment, floor space, etc. Many of the mistakes that have been made in heat-treatment installations are due to the fact that the problem has been considered from the standpoint of fuel alone or of the first cost of installation. Such a view is short-sighted, for the cost of fuel alone makes up but a comparatively small part of the total production cost. But when these items are considered in their proper place with the other items of operating cost and with the proper inter-

pretation of the relation of these to the cost of the finished product, it will generally be found that the cost of fuel and the cost of installation become of secondary importance in measuring or setting a standard of excellence to which the product must conform. In other words, the ultimate aim of any heat-treating process, from the economic standpoint, is to obtain *the best heating of the product at the least total cost.*

**The Standard Heating Unit.**—There is no definite standard employed for the measurement of production cost in industrial heating, as with power or light, because the conditions are continually varying and there is no one definite point or method to determine the cost. In power the test is the cost per brake horse-power hour at the shaft of the machine, irrespective of the purpose of the apparatus. In light the test is the cost per candle power hour, irrespective of the fuel employed or the means of utilizing or applying it. In electricity it is the kilowatt hour measured at some definite point. The nearest approach we can make to a standard for the commercial determination in industrial heating is to suggest—“*the cost per unit of quantity of given quality.*” This is somewhat indefinite and difficult of location, owing to the many different standards for quality and the great latitude in furnace design which affects the elements entering into the cost of production above noted.

Such a standard means the abandonment of the technique of combustion and other thermal considerations that are usually followed. It means that the cost of finished product is paramount, regardless of fuel cost. And it makes a point of considering first of all the application of heat to the stock, and then an efficient method of handling that material. Working along these lines has produced real results in heating efficiency (if such a term is permissible) with oil fuel; the gas fraternity are beginning to recognize the basic truth of the statement that fuel cost does not determine heating cost; and the electrical men are slowly falling in line. Each fuel has limits within which it can be used, and *these are determined by the nature of operations regardless of fuel cost.*

**Heating.**—Any talk upon industrial heating must necessarily take into account the right fuel and its proper application, a suitable furnace design and construction, and a proper layout and efficient handling of materials. Although each of these propositions is, in a sense, distinct, it is obvious that each involves and must be co-ordinated with the others. Similarly, the broad subject of heating must deal with:



- (1) The generation of the heat—the fuel;
- (2) A system for applying the heat—the furnace;
- (3) The utilization of the heat—the uniform heating of the stock;
- (4) The conservation of the heat—guarding against losses.

**Comparative Fuel Costs.**—The comparison of initial fuel costs is always an interesting subject, but unless it is carefully amplified and taken only in “small doses,” it is apt to prove the truth of the old saying that “a little learning is a dangerous thing.” All of the factors given in the previous paragraph must be considered in the selection of any fuel, for, after all is said and done, it is the cost of heating as shown by the finished product, and not the B.T.U. cost of fuel, which counts the most.

The chart given on page 176 illustrates graphically the relationship between commercial fuels, based on their heat unit cost.

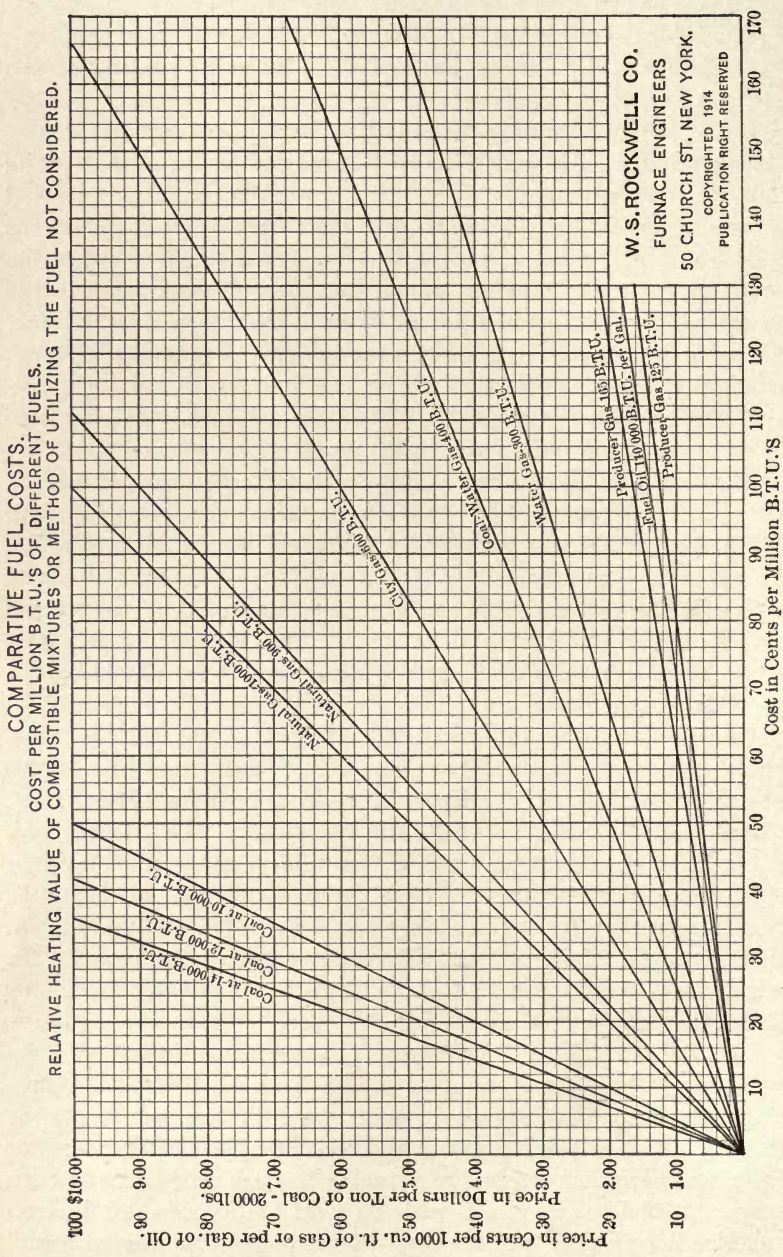
This chart facilitates the determination of the cost per million B.T.U.'s of commercial fuels at different prices; the relative prices for different fuels at a definite price for one fuel or per million B.T.U.'s and so forth.

To illustrate—the cost per million B.T.U.'s would be: at 3 cents per gallon for fuel oil—21.5 cents; at 20 cents per M for 1000 B.T.U. natural gas—20 cents; and at \$5.00 per ton for 12,000 B.T.U. coal—20.8 cents.

Again, at \$5.00 per ton for 12,000 B.T.U. coal, the relative prices for the other fuels, keeping the same B.T.U. cost, would be—\$5.80 per ton for 14,000 B.T.U. coal; 21 cents per M for 1000 B.T.U. natural gas; 12.6 cents per M for city gas; 2.94 cents per gal. for oil; 2.6 cents per M for 125 B.T.U. producer gas, etc.

Further—at an assumed cost of 30 cents per million B.T.U.'s, the relative prices for various fuels would be—4.2 cents per gal. for oil; 5 cents per M for 165 B.T.U. producer gas; 9 cents per M for water gas; 18 cents per M for city gas; \$6.00 per ton for 10,000 B.T.U. coal, etc.

**The B.T.U. Value.**—The fancy of selecting a fuel merely by its B.T.U. value alone, however, should be self-evident. To illustrate, take the case of anthracite coal: when broken into pieces the size of a man's fist it is used in the ordinary hot-air “heater” or house furnace; when crushed to a smaller size it is used in the kitchen stove; crushed to rice-size it may be used for forced-draft boilers; pulverize it to a dust and it may be used in the “powdered coal” systems. But would the furnace size be suitable for the kitchen





stove, or would stove coal satisfy the conditions necessary for the latter systems? Assuredly not; and yet the B.T.U. value of the coal remains absolutely unchanged. In other words, it is not the cost of the B.T.U.'s in coal, but all in the manner of its use.

**The Combustible Mixture.**—Again, the so-called B.T.U. comparison of fuels, which has long been generally accepted as standard, is misleading. In fact, it is not the B.T.U. value of the fuel, but the B.T.U. value of the combustible mixture that counts. There is not as much difference in the heating value of the combustible mixtures of the various gases as there is between the heating value of the gases themselves without considering the combustible mixture. For example, if city gas were assumed to be 600 B.T.U. and producer gas 120 B.T.U., the heating value of the gases would generally be considered in the proportion of five to one; and many comparisons are made upon this basis. In practice, however, whether it be in an internal combustion engine or in a furnace, the actual values of the fuels are not anywhere near the ratio of five to one; if they were, then an engine of given size cylinder which would develop 100 H.P. with city gas would only give 20 H.P. with producer gas. This comparison most people would agree is ridiculous and unreasonable on its face, in the light of practice in power; and yet the same people do not hesitate to draw such a comparison when considering heat, although the determinative conditions are just as true in one case as in another.

**The Right Fuel.**—The generation of heat for heat-treatment purposes involves the proper application of the right fuel. Superficially the choice of fuel appears to be a simple one. Too many persons, however, are prone to select off-hand some fuel such as coal because the initial cost is low, or maybe natural gas if it is near at hand, or even electricity just because it sounds attractive and is easily controlled. Although each of these in its proper sphere would be the logical source of heat, as general proposition no one fuel is appropriate to every case. Neither low initial cost, nor local supply, nor ready control sums up the situation. These are but factors in the case as a whole, and the value of one fuel cannot be measured by its use in the way another fuel would be used. There is always a *right* fuel for the particular work in hand, so that each problem must be thoroughly studied and understood if the best solution is to be had.

**Fuel Efficiency.**—There is, or at least should be, no argument on the fuel question. The relationship of the various fuels is fixed



by physical law and commercial conditions. The term "fuel efficiency" is not used in power nor in domestic house-heating work; and neither does it exist in industrial heating. Generally speaking, it may be assumed that any difference in results between oil, or gas, or electricity for heating furnaces should be attributed to the manner in which the heat is applied to the stock and not to any inherent advantage in one form of energy over the other. It is not proper to say that oil is cheaper than electricity or coal or gas, or vice versa, or that a higher-price fuel can displace another because the former is "more efficient." There is no such thing as that one will do more than another. It is the nature of the operation and the manner of applying heat that counts, and not the fuel. Thus, the manner of its use may be efficient or the means of employing or utilizing it, but certainly not the fuel itself. It can be said that electricity in a given type of furnace will produce a better result than oil in a given type of furnace, but it will be noticed in so doing that it is the difference in the manner of applying the heat, which is equivalent to a difference in furnace design, that determines the result, and not to any advantage in one form of energy over another. The term "fuel efficiency," therefore, is misleading in that it is employed to express a condition that does not exist.

**Fuel vs. Operations.**—It may be said that the extent of the heating operation more or less determines the fuel. It would be good practice to employ city gas for the annealing of a small quantity of wire in a loft building; and with a larger quantity and other working conditions the fuel might be oil; but if the operation be conducted on a still larger scale, as in a rolling mill where the size and type of furnace will so permit, then the fuel might be producer gas or coal. Thus, city gas at \$1.00 a thousand for many operations might be recommended in preference to oil at 1 cent a gallon, and electricity at any price in preference to oil or gas at any price. In annealing, for instance, we might use oil for certain results and in same room use coal for annealing the same metal, but for different results. Thus the nature of the operation more or less determines the working limits, regardless of fuel cost.

**The "Fluid Fuel."**—We can even go a step further and state that no one fuel has a monopoly on uniform heating, or control, or economy. At the present time there are many furnaces of good design, operating on cheap coal, which produce a better quality of product at less cost and maintain more uniform temperatures, with more accurate control, than other furnaces of poor design built

for the same purpose, using either oil or clean-washed producer gas. All other things being equal, a "fluid fuel" (as distinguished from a solid fuel) is generally to be preferred, as it lends itself more readily to accurate control. Ordinarily it would be assumed that a fluid fuel would permit of greater flexibility of operation than a solid fuel, and it invariably will when all other conditions are equal. However, as previously noted, there are many cases where the advantages of the more flexible fuel are lost with inefficient means of utilizing it. But it is misleading to couple any fuel with the term Uniform Heating, or Control, or Economy, without specifying or qualifying the manner in which it is to be used. It is the manner of applying the heat and not the fuel which thus determines the success or failure of the operation.

**Selection of Fluid Fuel.**—Even the selection of a fluid fuel is dependent upon conditions other than heating value or composition of the fuel itself. For instance, we might consider a very small furnace for annealing, tempering or hardening small pieces of stock. There would seem to be no question but that gas would be the fuel most generally preferred. But even the selection of the gas itself would be dependent upon conditions other than that of temperature control. To illustrate: while one might use either producer gas, water gas, city gas or natural gas in the case just mentioned, it would not follow that each of the fuels could be considered if the operation was one requiring a very high temperature, such as welding. The same conditions would hold good if the operation was one requiring a very low temperature, such as japanning. If, however, the operation were to be conducted on a large scale, and one involving the use of a large furnace in which there would be ample room for combustion, there would be brought into competition with these gases a liquid fuel in the form of oil, which, by reason of the latitude afforded in furnace design, could compete from the standpoint of temperature control; and, depending upon the market, it might compete in the matter of price.

**Influence of Working Conditions.**—There is generally a confusion between the terms Uniform Heat Distribution and Uniform Fuel Distribution; the two do not necessarily go together, although at times they do. For instance, in the case of japanning, requiring a low temperature, particularly in small and medium-size ovens, a fluid fuel in the form of gas is generally preferred. The reason for this is that the fuel may be applied on all sides of the oven and burned in small quantities at different points. This could not be as readily



done with a liquid fuel like oil, which by reason of its great calorific power and lack of control when burned in very small quantities in a very limited space, would prohibit a distribution of the fuel in the manner usually provided for gas. If the oven were large and there was plenty of room for combustion and distribution of heat through flues, it would be possible to approach the same conditions of uniform heating, as far as the stock is concerned, without uniform distribution of fuel. In one case the result of heating the material is accomplished by distributing the points of heat generation, while in the other it is produced by localizing the point of heat generation and distributing the heat after it is generated. This goes to show why working conditions are, as a rule, determinative not only of the fuel, but of the manner in which it may be employed. Also, to show that the conclusions formed in one case may be reversed in another, when a change in working conditions makes it either possible or desirable, even though there be no change in the composition or price of the fuels themselves.

**Regeneration.**—The question of regeneration or recuperation is usually misunderstood. Recuperation is generally commercially desirable on general principles, but there are times when it is physically necessary, irrespective of the economy of the operation. For instance, neither hot nor cold producer gas is suitable for high forging or welding heats in furnaces without regeneration or recuperation, because the heating value of the fuel is so low. Because of their greater heat value, water gas, natural gas, city gas or fuel oil might be used for operations with which producer gas could not be considered, for the reasons given above. But if the furnaces were large and the principles of recuperation could be employed, then the producer gas could compete, and the extent to which it could compete would be determined by fuel cost coupled with the manner in which the fuels were employed. Very often a comparison is made with producer gas used in this form against the other fuels to show that the gas would be the cheaper. But this in itself is not conclusive unless the determination is based upon the results secured by the use of the other fuels in a manner which would involve recuperation, and in this way take advantage of every possible saving. Producer gas, as a rule, would show the highest efficiency from the standpoint of recuperation, because the volume of the inert or non-combustible gases is greater; but it does not follow that this efficiency of recuperation is in itself determinative of the fuel.

**Cost of Delivering Fluid Fuels.**—Even though fuels were com-



pared in the manner above indicated, it would not follow that the result would be as conclusive from the standpoint of industrial heating engineering as it would be from that of fuel. The reason for this is that some fuels by their very nature are better adapted to the manipulation of conditions governing a manufacturing process than others. For instance, fuel oil, or any cold-washed gas that could be delivered to a furnace through pipes, and thus distributed to scattered units throughout a plant, could be more easily handled than producer gas delivered in a hot state through a flue.

**Cost Factors with Producer Gas.**—The conditions that hold good with an open-hearth furnace do not obtain in a small forging or heat-treating installation made up of scattered units. There is no question but that the B.T.U. cost at the producer is less with hot gas than with cold washed gas, because of the heat loss in the latter in the processes of scrubbing, drying and cleaning. On this comparison of B.T.U. cost at the producer much has been written and many claims have been made for superiority one way and another. It must be borne in mind, however, that in industrial heating it is not the cost at the producer or at the point of fuel supply that counts, but rather the cost of the finished product at the delivery end of the furnace. This heating cost, as it might be termed, takes into account not only the fuel at the furnace, but the utilization of the fuel in the furnace; and on top of this, the labor and any other charges, such as interest and depreciation, that may be legitimately charged against the equipment itself. The fuel, at best, is secondary and not of the paramount importance which many have erroneously tried to make it.

**Fuel Equipment.**—In the cases of such artificial gases as producer gas, water gas, etc., the cost of the necessary plant equipment for their manufacture, besides interest and depreciation, must also be figured in with the cost of the gas. It is evident that the heat-treatment plant must be of considerable size to warrant a large initial plant investment for the manufacture of such gas. Similarly, if oil is to be used, there must also be an allowance for storage tanks for protection against poor deliveries and unusual service demands. The cost of piping for fuel distribution is lower in the case of oil than with gas, as smaller pipes are used.

**Fuel Supply.**—The selection of a fuel involves not only its heat-unit value, but a consideration of local conditions of constancy of supply and of sufficient quantity without undue fluctuation in price. The source of fuel supply must be absolutely dependable, both in regularity of deliveries and uniformity of fuel. This item is largely

connected with the use of oil and is a phase of the fuel question well worth studying. Thus, in considering the availability of any fuel, the locality, natural resources and freight should be taken into account.

**Uniformity of Fuel.**—High quality of product requires uniformity of heating, and which in turn requires uniformity of fuel. Such a product may be obtained only by having an absolute control of the volume, temperature and composition of the gases to and from all points of the chamber. Any changes taking place in the composition of the fuel not only makes the work of the furnace man more difficult and exacting, but also must inevitably result in intermittent heating and unsteadiness of operation. That is, variable supply or non-uniform fuel is not conducive to good product. In this connection it is advisable to note that the presence of sulphur—as in producer gas or coal—is more or less injurious to the metal when at high temperatures, as it has been shown that hot steel is capable of being sulphurized as well as carburized.

**Fuel Oil.**—There is probably no one fuel that has been more abused than fuel oil. Its great concentrated heat value and flexibility of application and control have been, commercially, its greatest drawback, for the reason that these advantages have permitted the application of the fuel in a haphazard manner by people who seem to be satisfied so long as it was burned and made heat in some form or other. Even many of the manufacturers of oil-burning equipment are not entirely free from this criticism. Much of the competition which has been held against fuel oil, and comparative statements of operating costs that have been made up, are not based on an efficient use of the fuel at all.

**Air Control with Fuel Oil.**—The majority of heating equipment installed with oil are lacking in some of the very elementary essentials necessary for good combustion, and in this respect are not anywhere near as efficient as an ordinary kitchen stove. There seems to be an absolute disregard of the fact that it is just as necessary to control all of the air entering into a furnace with oil fuel as it is with gas or coal. Most city gas equipment has this provision, as have boilers or ordinary stoves, but it seems to be entirely lacking with most oil-burning equipment, although the reasons for it are just as important in one case as in another. The common practice is to inject oil in a hole through the side of a furnace; and many people think that because there is a valve on the oil and air lines that they consequently control the air. This, however, is not true, for the



reason that in many furnaces by far the greater proportion of air required for the combustion of the fuel is "induced" by the force of the blast and does not pass through the burner itself. It has been by reason of such conditions that oil has been abandoned and given a bad name in many places where the conditions would be reversed if it were properly handled.

**The Human Element.**—Thus the average man, when he sees a kerosene lamp smoke and blacken the chimney, or a gas mantle puff and impair the light, will ordinarily recognize that something is wrong, and immediately make the adjustments necessary to overcome the difficulty. Both of these are the effects of a common cause—the improper mixture of the fuel and air necessary for proper combustion; and in making such adjustments, whether he knows it or not, he is merely establishing the proper relationship between the fuel and air necessary for good combustion.

Yet we will find this selfsame man, day after day and year after year, operate or permit others to operate, at great expense, furnaces with oil or gas which smoke and puff and pollute the atmosphere with hot and obnoxious gases, but never think of making the adjustments necessary, which are the same as those required in case of the lamp. Such a man is either not "on the job" or his furnace is lacking in the essentials for good combustion common to every household lamp or stove, whether it burn oil or gas or coal. Yet the majority of men employed in heat-treating work, as well as a large percentage of furnaces, particularly those fired with oil or coal, are open to this criticism, which is evidence of the necessity for improvement in the personal element, at least to the extent of either making the adjustments if provision for such is on the furnaces, or at least to insist that the furnaces be designed on the A.B.C. principles of heat generation. And when such adjustments are made with proper furnaces, the operator benefits himself by decreasing the heat and gases affecting his health and comfort, and benefits his employer in turning out better product and saving fuel and power and conserving the life of his furnace. Such conditions, which actually exist in the majority of shops in the country, are a sad commentary on the work of efficiency, safety first and industrial betterment ideas so prevalent at this time, and sustain the point that we often look at and do not see opportunities for improvement that can be made in a simple way. The average furnace operator appears to act on the principle that he is not making a good showing unless he has plenty of smoke and flame belching out of every crevice of the furnace—probably for the same



reason, or lack of reason, responsible for the blacksmith striking two blows on the anvil to one on the horseshoe.

It would appear only reasonable to assume that the existence of such conditions in the shop does not permit the owner of such shop to make the statement that one of his most important manufacturing operations—i.e., the heat treatment of good steel—is conducted under the best possible methods with the best possible furnace equipment by the highest grade men, or that it is even on a par with the average machine-shop practice. And all this notwithstanding the evidence that may be offered in the way of "Temperature Records" or "Fuel-burning Equipment" in an attempt to sustain the point.

It is invariably cheaper to do it right. The extra expense involved in furnaces of heavy construction with proper provision for applying heat to the chamber and for removing it from the chamber, is insignificant when compared with the saving effected.

**The Value of the Furnace Operator.**—If, as generally conceded, men are paid in proportion to their skill and the part that such skill plays in the make-up of a finished product, then a good annealer is worth more than a roller in a rolling mill, and a good man in charge of heat-treatment work is worth more than an automatic machine operator in an automobile or machine shop. In one case the man operates a machine and it is a machine that more or less determines the result, and at any rate they are a mechanical check on the operation. In the other case it is purely a question of skill, experience, and judgment, with no mechanical check upon the major part of the operation. The furnace and all auxiliary appliances are but tools, and while it is necessary that they should be of the best, they are nevertheless but tools in effect and bear about the same relation to the result that a good tool in the hands of a good operator bears to any other result. Furthermore, it is the judgment of the furnace operator that determines if the work of all that have preceded him shall be spoiled or improved upon, and if the time, labor, and money spent to produce the results sought for are capitalized or wasted.

**Purchasing Brains.**—It has been stated that the average manufacturer will unhesitatingly invest money in anything involved in his processes of manufacture outside of the human element, which is virtually paying a premium on everything but brains. It is common practice to install an expensive machine, costing thousands of dollars, and employ a cheap, inefficient man to run it, notwithstanding that it is the man who controls the output and cost of operating that machine. When the relationship of the human element to the result

is of less importance, as, for instance, with a machine press—as it surely is when compared with a furnace—then there will be manifested the false economy effected by the employment of unskilled, inefficient operators. In the final analysis the machine or the furnace is nothing more than a tool in the hands of the operator, and the value of the human element depends upon the amount of skill that must be exercised in the use of a tool, whether it be a hammer, a chisel, a press or a furnace. There are many cases when it is permissible to employ unskilled labor in connection with a machine, where the operation is more or less automatic and the operator is required to do nothing more than start or stop the movement and feed material. Such a practice, however, is foolhardy with a furnace, because of the paramount importance of the human element in the operation. It is a waste of money to install efficient types of furnaces, which are necessarily expensive, without intelligent supervision over the operation in the form of at least one efficient man who can either operate it himself or direct its operation by others. The practice of employing at least one skilled man for such purpose is gaining headway and will undoubtedly continue to do so, as his labor is usually more than paid for by the savings effected in the cost of operation, to say nothing of the betterment of the product. A good furnace coupled with a poor operator does not make the proper combination, and when both are of inferior caliber, as they so often are, then it is unreasonable to suppose that the all-important heating operations are conducted as they should be, even though there may be some, but nevertheless weak, evidence in the form of pyrometer records to the contrary.

**Effect of Operation.**—The operation of the furnace in the shop should be regarded in the same light as the stove in the kitchen. The furnace operators should be taught that furnaces operate on the same principles as an ordinary house-heating coal stove; both must be given the proper attention in the matter of regulating the dampers for the air supply and flue gases in order to accomplish the same results. The importance of regulating the amount of air which is used for the combustion of the fuel cannot be too strongly emphasized. In this respect the ordinary kitchen stove is in many ways superior to many so-called heat-treatment furnaces. Just study the cook-stove in your own home and see how many different ways there are for adjusting the air supply and draft. To illustrate: under the fire there are usually one or possibly two dampers; directly over the fire there is another damper for checking the fire; another damper will



permit of the carrying of the heat currents around the oven (conservation); and still another damper or two will shut off the draft up the chimney. As a general question, how many heat-treatment furnaces have an equal number of devices for controlling the combustion or heating? Apart from the question of recuperation and its direct saving in fuel, there is involved the method of operation, and question of furnace design which in itself is modified by the method of operation. While in some cases the application of the fuel is poor, in others the construction of the furnace may be at fault or not adapted to the work it has to do.

**Furnace Design.**—Poorly designed furnaces are the cause of much of the difficulty and time spent in trying to account for poor results which could be better spent in insuring better conditions. Many furnaces to-day are operated with elaborate pyrometer systems, but with a complete disregard for the conditions that make good heating possible. There is no control of the air for combustion entering the furnace, no control of the waste gases leaving the furnace, and no knowledge of their composition or action while in the furnace. Under such conditions good combustion, with soft heats and uniformly heated stock, is out of the question. The object is not merely to burn fuel, or to make heat, but to apply the heat economically and effectively.

**Oil Burners.**—There is altogether too much importance attached to oil burners, both by manufacturers of such appliances as well as by users. Too many people have the idea that all that is necessary to do with oil is to buy an "efficient" burner and build a furnace around it. But there is really no such thing as an oil burner in the sense usually taken for a gas burner. The very term is a misnomer, as the oil burner is nothing more than a valve and its efficiency is mechanical and not thermal. In fact, the majority of oil burners are not, properly speaking, mixing valves, as most gas burners are, for the reason that the most successful burners are nothing more than valves which introduce fuel and air into the furnace in proportions fixed by the operator, the actual mixing taking place in the furnace and not in the burner itself. It does not matter as much how the fuel is delivered at the furnace as what is done with it after it is delivered in the furnace.

**Burner vs. Furnace.**—This influence which the design of the furnace—that is, the method of using the fuel in the furnace—has upon the economy of heating, regardless of the burner, is well brought out by the following chart, to accompany Figs. 94, 95 and 96.



Three different types doing the same work.

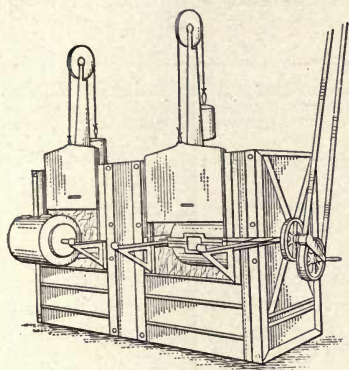


FIG. 94.—Externally Fired Cast-iron Tumbling-barrel Furnace (1898).

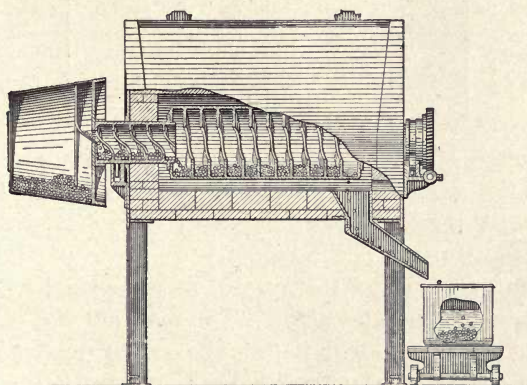


FIG. 95.—Externally Fired Cast-iron Helical-cylinder Furnace (1906).

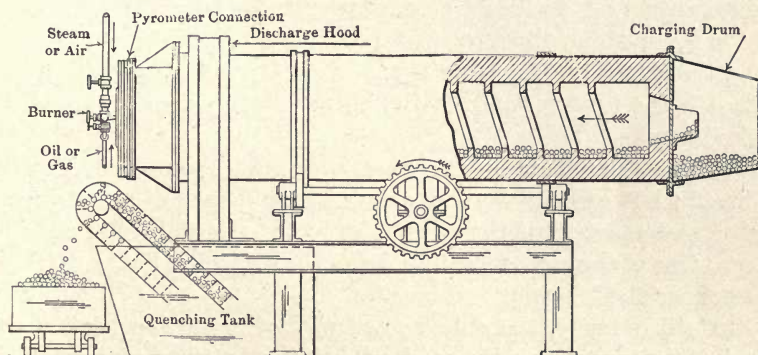


FIG. 96.—Internally Fired Tile-lined Helical-cylinder Furnace (1909).

The figures are taken from actual operation and weight of material and fuel.

Design of Furnace.	Externally Fired Cast-iron Tumbling- barrel Furnace, 1898.	Externally Fired Cast-iron Helical- cylinder Furnace, 1906.	Internally Fired Tile-lined Helical- cylinder Furnace, 1909.
Metal heated per hour	287 pounds	576 pounds	1450 pounds
Increase of metal heated per hour		100 per cent.	405 per cent.
Fuel oil burned per hour	6.41 U. S. gals.	3.64 U. S. gals.	3.48 U. S. gals.
Decrease of fuel oil burned per hour		43.3 per cent.	45.7 per cent.
Metal heated per gallon of fuel oil	45 pounds	158 pounds	416 pounds

In each case the pieces heated were of the same size and material and the lightest in individual weight of their kind. The figures represent three different types of rotary heating furnaces doing the same work. The advantage in favor of the internally fired helical furnace—Fig. 96—was still more marked when heating pieces of greater individual weight. The material was also of better quality, being freer from oxidation. The cost of repairs is also very much less for the internally fired helical furnace than either of the others.

Now these three furnaces were operated with the same burner, the same fuel oil, the same steam pressure for atomizing, the same air for combustion, the same material, the same temperature, at the same time, and by the same men. This then illustrates the point that it is the furnace and not the burner alone which produces the desired results.

**“Quality of Heat.”**—Much has been said about “the quality of heat”; but as heat can differ only in the degree of temperature, such a statement must therefore refer to the atmosphere in the furnace. One of the most recent books on the subject of heat treatment of steel has the following statements:

“Until recently, the only known way of producing heat of the required intensity was by combustion—the burning of some fuel. The attendant disadvantages of this are well known. The crude

open coal forge is capable of heating the steel, but leaves much to be desired as regards the quality of the heat, its uniformity, and the temperature control. In order to produce heat at all, the carbon in the coal must be combined with the oxygen of the air, and a strongly oxidizing flame is unavoidable. The steel exposed to this action, or to the inevitable results of it, suffers accordingly. The coke-burning furnace offered some improvements, but only in detail. Now there are highly perfected furnaces for burning oil and gas, and some of these offer still further advances, but the principle at the basis of all of these is the same—there must be a ‘burning’ process to produce the heat; oxidation must be present with all fuel-combustion furnaces.

“Through what means, then, may we obtain the proper quality of heat, uniformly applied, and of the right degree? The electric furnace for the heating of steel brings the answer. It overcomes most of the objections to the ‘combustion process’ by introducing a new principle.”

Further on the statements are made: “The atmosphere in the heating chamber of the electric furnace is inherently ‘reducing’ in its nature, due to the fact that the hot carbon plates absorb all of the atmospheric oxygen. By raising the door slightly, and opening the draft-hole at the rear, a slight current of air may be admitted which will counteract this tendency. Leaving the door open slightly more would allow an excess of air to enter, so that an oxidizing atmosphere could be produced. Between the extreme points fine shades of atmospheric conditions can be obtained. Thus the quality of the heat can be absolutely and easily regulated.”

**Furnace Atmospheres from Combustion.**—Commenting on the above, the question of atmosphere in the heating chamber is one of operation of the furnace, assuming the proper furnace design, and simply comes down to the relation between the fuel and the air supply. In the design and operation of the best types of heating furnaces it is the aim to produce an atmosphere, under pressure, which virtually contains no oxygen and only a very slight amount of reducing elements. Take for example the under-fired type of furnace, properly designed and operated. The actual combustion of the fuel takes place in the separate chamber under the hearth where the amount of air taken into the furnace is just sufficient to produce perfect combustion of the fuel. By the time the hot gases actually reach the heating chamber they are thoroughly mixed and, on account of the design



of the furnace, a pressure is built up. This pressure stops any inflow of free oxygen through the doors, and otherwise surrounds the steel with the neutral atmosphere of hot gases. That these hot gases may actually contain no oxygen and very little reducing vapors is well shown by the following analysis:

	Per Cent.
Carbon dioxide.....	12.5
Oxygen .....	0
Oil vapors.....	0
Carbon monoxide.....	2.1
Nitrogen.....	85.4

From a study of this analysis, which was taken under ordinary operating conditions of a well designed furnace and without the operator knowing that anything unusual was expected of him, it certainly cannot be said that the "combustion process" produces, under proper conditions, anything but a proper neutral atmosphere.

**Furnace Atmospheres with Electricity.**—In contrast with this, consider the effect taking place in the electric furnace previously referred to. In this case the heat is virtually supplied outside of, and through, the walls of the chamber. Free access of unaltered atmospheric air to the inside of the furnace exists, and coming in contact with the heated steel results in a very rapid oxidation of the metal. An attempt is sometimes made to remedy this condition by introducing charcoal into the chamber with which the oxygen is supposed to combine to form an inert atmosphere of carbon dioxide, or even by exposing the carbon electrodes of the electric element and allowing the oxygen present in the chamber to attack them and thus consume the free oxygen. It must be realized that if this elimination of the free oxygen thus occurs it must take place in the furnace itself and in the chamber where the stock is being heated and the steel is therefore more or less exposed to oxidation.

The argument previously advanced that the atmosphere in the electric furnace may be controlled by slightly raising the door and opening a vent in the back of the furnace is entirely contrary to heating principles. The cost of the heating itself advances when this takes place because cold air is entering through the front and the heat is allowed to flow out through the vent. Such a proposition is analogous to the effort of trying to heat a house in the winter with the doors open.

**Electricity for Heating.**—The advantages of electricity as a source of heat compared with oil or vice versa are determined only by the nature of the operation regardless of fuel cost. Each form of energy has its own field of use. When it is considered that fuel oil under proper application is continually being used within temperature limits of 10° F., it must be evident that electricity must offer some powerful indirect advantages for a great deal of heat treatment work in order to be given a chance. On the other hand, there are, however, many cases like the open-hearth, reverberatory and other forms of heating where the limit has been about reached with fuel. It is in such operations where electricity, by reason of a better method of applying heat to the stock, can overcome the disadvantage of higher fuel cost with less actual energy for the operation. Thus we might also designate certain forms of chain welding as good examples where electricity might be advantageous.

**Fuel vs. Product.**—Reduced to lowest terms, heat generation is an economic problem. Commercial heat treatment requires the production of the best attainable results at the lowest cost. We may sum up the fuel question by stating that in connection with appropriate furnace design and furnace operation, that fuel should be used which will cost the least viewed from the standpoint of *finished product*. This cost not only applies to increased output, but also to the quality of the product. The former results in lower manufacturing costs; the latter in greater efficiency and higher selling prices.

## CHAPTER IX

### HEAT APPLICATION

**Furnace Equipment in General.**—The usual consideration of furnace equipment for heat-treatment operations is based on requirements of "accurate temperature," "heat control," "temperature variation," etc., with the result that the trade literature—which is the catechism of many, if not of the majority interested in the work—has developed a standard of heating which is altogether too low and must be superseded by one based on a broader view of the problem in order to effect greater progress.

The existence of such a standard is probably due to the reasoning—"that a uniformly heated piece naturally involves a uniform temperature within the furnace, and the less the variation in temperature the better the results will be; therefore, in order to produce a uniformly heated product it is necessary to employ a furnace that will produce a uniform heat with minimum variation of temperature." The natural result of such reasoning has been a development of pyrometers to indicate the variations in temperature, and the development of many different designs of furnaces which have been vigorously and extensively exploited on the strength of claims for "accurate temperature control," "minimum temperature variation," "neutral or reducing flame as desired," "no oxidation," etc.

That phase of the work covering pyrometry has been of inestimable value and is more highly developed than nearly any other branch of heat-treatment work. It is, however, unfortunately too often considered as an end when in reality it is but a means to an end—a means which if properly employed will indicate the simple principles back of "heat application," as in comparison with "heat generation" or "heat utilization."

The standard of heating requirements, with a means in the form of pyrometry to check them, has developed much discussion of the relative merits of the different designs of furnaces offered to meet them. Much of this has been directed towards the claims made for the furnaces supported with evidence in the form of pyrometer charts,



heat logs, and other data incident to the indication of heat, tending to show the ability of the various designs to meet the heating requirements above outlined. This is all right as far as it goes, but it does not go far enough. It may be considered as "evidence" of a heat condition in some part of a furnace chamber, but not necessarily as "proof" of a uniformly heated product within that furnace chamber. If it were otherwise, then we would have not to deal so often with variations in the finished product without any apparent variation in the indicated temperature. Heating a furnace chamber uniformly, and uniformly heating a product within that furnace chamber, are two distinct operations. The former must accompany the latter, but the mere indication of the former does not by any means prove the existence of the latter. It does not follow that the temperature variation indicated in any two points in a chamber when empty will be the same as that indicated when the chamber is partially filled, or more particularly, when it is filled to full normal capacity. The real test of a furnace for a given operation from the standpoint of uniformly heated product, is not the temperature variation when the chamber is empty or partially filled, but the *temperature variation around the mass to be heated when the chamber is loaded to full capacity.*

This is a simple fundamental rule which, when considered with reference to a given operation, illustrates why it is possible to secure better results in finished product with one type of furnace over another without any apparent difference in the indicated variation in temperature at any given point.

To illustrate: Let us consider two gas-fired bake-ovens of the same size, each designed to accommodate six cakes of a given size, the essential difference between the two being that one is heated by gas jets at the bottom, as in Fig. 97 (a), and the other by gas jets at the top, as in (b), the problem being the uniform heating or baking of the six cakes to be placed on the tray *x*.

If a thermo-couple should be introduced at any two points on the tray *x* in the empty ovens, it will be found that the heat will be fairly uniform with either design, even though with one design the actual oven temperature may be different from the other. It is reasonable to suppose that one small cake, as in (c), would compare favorably with (d), as there is ample room for circulation of the heat from one side to the other. We have in one case (*a* or *b*) an indication of a uniform chamber temperature, and in the other (*c-d*)

an indication of a uniform chamber temperature and of a uniformly heated product.

Now suppose that each oven is filled to normal capacity, as in (e) or (f). If the space between the pieces is small, it is very likely that, in a given time, a given temperature will produce a color on the side of the cake nearest the fire that will be different from the color

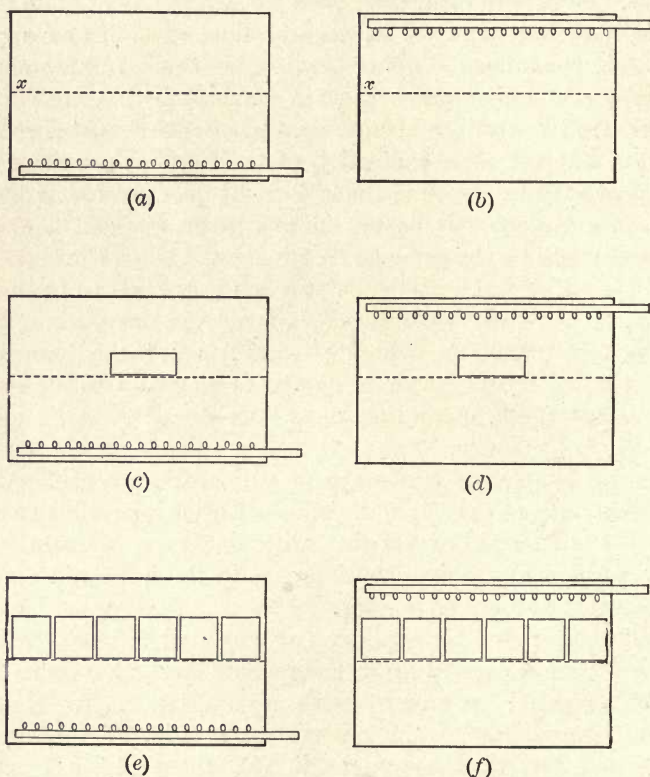


FIG. 97.

on the opposite side. It is also likely that the variation between any two points on the same side of the tray will be very slight, but that the variation between the under and upper sides of the tray will be considerable. This indicates the possibility of turning out a product not uniformly heated from a chamber that may be uniformly heated when empty, or but partially filled, and at the same time constantly indicating a uniform temperature on any lateral plane.

This illustrates how weak and irrelevant such claims as previously noted are to the real question—the uniformity of the heated product. The very manner of placing the stock in the chamber may affect the final result. Uniform temperature in the chamber is a part but not all of the process. It is the peculiar conditions or requirements of each case that determine the type of furnace to use and the manner of heating the steel in it. There is no such thing as an ideal furnace for heat treatment any more than there is an ideal engine or fuel for power, for in one case as in the other, the point is determined by the working conditions.

**Heat Application.**—Heating a piece of steel, boiling a cup of water or baking a potato are alike heat-treating operations, and in so far as each leads to an absorption of heat, they are comparable. A cup of water will boil much sooner if the heat is applied from the bottom rather than from the top downwards. In the ordinary gas stove the oven is heated from jets below, while these same jets deflected downwards heat the broiler from above; a potato in the oven is heated evenly through to the center without burning the outside, but a potato placed on the broiler is burned to a crisp on the top while the center remains hard and uncooked.

Many carburizing boxes give evidence of having been “broiled” rather than “baked.” Boys still roast potatoes in open bonfires; men still heat steel in open smith-fires; and the results are about the same. An inefficient plant means that the product seldom reaches and never maintains the standard to which it is entitled, and also that the cost of up-keep and labor far outweigh any difference in first cost of plant.

To make results harmonize with the requirements in each case requires furnaces of the best possible construction, fuel that would cost the least viewed from the standpoint of finished product, and it further requires that these furnaces be so arranged and such methods devised that the material may be heated and handled with the least labor and loss of time.

Only when this harmonious combination of suitable furnaces, right fuel, proper furnace layout and efficient material handling conditions has been secured can there be accomplished the best heating of a product at the least total cost.

**The “One” Furnace.**—One often reads of the claims of furnace manufacturers that this or that furnace is the “only one” for heat treatment. This is all wrong, as there is no one type of furnace for heating any more than there is one type of building for machine



operations. There are certain principles of construction, heat generation, application or utilization that, when properly combined, make up the right furnace; but it is always the local shop conditions that determine how these combinations should be effected. There is as much more experience and skill required for the determination of a furnace design than in building it, as there is between an architect and builder or carpenter in the design and erection of a building.

**Furnace Guarantees.**—One would not think of asking a stove manufacturer to guarantee good cooking with his stove, and it is as unreasonable to expect, as it is foolish to offer, a furnace guaranteed for good heat treatment without the proper handling. The right furnace, like the right stove, only makes it possible; and it is the man, like the cook, that determines the final result. What is most needed at this time is a better appreciation of heat application to useful work, as removed from heat generation, combustion or utilization. There should be more study given to the absorption of heat by the product and the manner of placing and handling to secure the best heating results.

**Uniform Heating.**—The problem of applying heat to industrial work is but a cooking operation, like the baking of bread; the bread must be heated uniformly throughout. Similarly the charge in a heat-treatment furnace may be best heated when it has opportunity to absorb heat uniformly from all sides. And as far as the heat absorption is concerned it does not matter whether this heat is supplied as radiating heat from the lining of the furnace or through the direct application of hot gases. Except in the case when electricity is used as the source of heat energy, it may be said that the majority of commercial heat-treatment furnaces involve the application to the work of hot gases obtained through a combustion process. If it were then possible to apply this heat so that the charge would be equally and simultaneously heated on all sides the general ideal condition would be met.

**Underfiring.**—In principle,<sup>1</sup> it is best to apply the heat first to the bottom of the charge. It is natural law that heat or hot gases tend to rise—a very simple and important fact and yet one so frequently overlooked in industrial heat application. Further, since in practical, every-day work the height of suspension of the charge (in order to provide for circulation around the entire mass) is more or less reduced to a minimum, and which necessarily results in the

<sup>1</sup> We say this, because we will show later that certain conditions may entirely reverse this in practice.—AUTHOR.

major part of the charge to be heated being near the hearth or even laying directly upon it, we may consider that the best construction in general to adopt is to place the initial heat where it is most needed—which is under the charge. As much advantage as possible is then taken of the natural law of hot gases rising in effecting a further application of that heat to the sides and top of the charge. This, in effect, is underfiring.

**Simple Underfired Furnace.**—A common type of heat treatment furnace is illustrated in Fig. 98. The heat is generated in the combustion chamber under the hearth, supplying heat to the hearth. The hot gases then rise upon either side of the hearth to the roof, where they become mixed or equalized, and then are forced down upon the floor of the chamber by the pressure which has been built

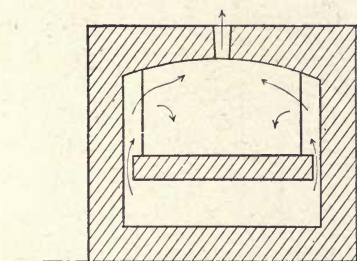


FIG. 98.

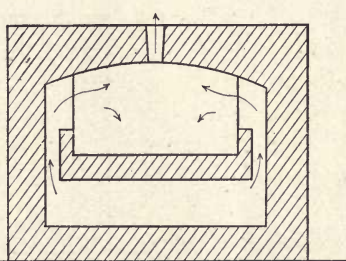


FIG. 99.

up. In the type of furnace shown it will be noted that the furnace door opening is the same height as the roof arch, and that there is also a vent located in the roof. Such a design is permissible for small furnaces built upon legs to lighten the weight for transportation, and where first cost is an important feature.

**Side Ledges.**—One of the objections to this common type of furnace is the inherent tendency to overheat the sides of the hearth. As the hot gases sweep upwards from the combustion chamber towards the roof the sides of the hearth will become hotter than the central area, with the consequent superheating of any material placed at the sides of the furnace near the ports. To overcome this tendency to localized heating, the sides of the hearth are frequently protected as illustrated in Fig. 99. Such an arrangement affords plenty of room for circulation at the sides, tends to prevent cutting action near the floor line and automatically stops any overloading at the sides of the furnace.

**High Ledges.**—It was originally thought that the flow and heat transfer of the hot gas currents would be in an underfired furnace, as in Figs. 98 or 99, from the combustion chamber to the hearth and the metal on the hearth, and thence to the roof. It was then thought that if the hot gases, after leaving the combustion chamber, could be made first to travel to the roof, be thoroughly equalized, and then be brought down to the hearth, that a more uniform heating of the charge would result. The furnace in Fig. 100 shows an early development of the underfired furnace in a misguided attempt to do this. The side ledges were made to reach nearly to the roof so that the gases had to go there directly after leaving the combustion chamber. Experience with furnaces of the type shown in Fig. 100 soon showed, however, that the hot gases—following natural law—

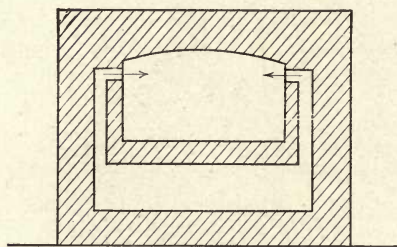


FIG. 100.

would first go to the roof whether these high side walls were there or not. In other words, they were proven to be not needed.

The second advantage hoped for through the high ledges in Fig. 100 was entirely to prevent any localized heating at the side of the charge. But it was then discovered that the small opening between the top of the ledge and the roof arch tended greatly to increase the velocity of the gases as they entered the heating chamber—that is, to form a blast action at the top of the furnace. Thus, if the charge were anywhere near the height of the door opening, a localized heating at the edges and top of the charge would at once result. For this and the previously mentioned reasons this type of furnace (Fig. 100) is not generally used now.

**Roof Vents.**—It will be noted that in the furnaces in Figs. 98 and 99 there is a vent in the roof arch, and while this is general practice, it is not good. One writer, in discussing this point, states that “as only approximately 20 per cent. of the air for combustion is



oxygen, the balance is inert gases which unfortunately must be heated to the temperature of the furnace and *expelled as quickly as possible*. In a scientifically designed furnace, this is readily done by the aid of the burner. If allowed to pocket or remain stationary in any portion of the furnace, the inert gases cause uneven temperatures. “. . . The vents for the escape of . . . the consumed and inert gases should always be located in the oven roof or arch.”

In the first place, that writer evidently loses sight of the fact that, with perfect combustion, all the gases become “inert” (assuming that he means a non-supporter of combustion); and that the furnace and stock are principally heated by the blanket action of hot gases. He admits that these gases are hot, but then reasons that because they are hot and inert they must be “expelled as quickly as possible.” But why throw heat away? In other words, he

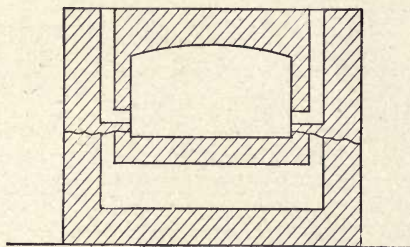


FIG. 101.

believes in *trying to heat his house in winter time by throwing open the skylights or windows!* He fails to perceive that with an open vent in the roof the hot gas currents will tend to short-circuit directly from the combustion chamber to the roof and discharge at the maximum chamber temperature. (Incidentally, exactly what part the burner—which is merely a valve for injecting oil into a furnace—plays in this ejection is not mentioned.) But by eliminating the vent in the roof the gases are given ample opportunity thoroughly to mix in the upper part of the chamber and are then forced down as a blanket at a reduced velocity upon the stock. This same pressure, as we have explained in the previous chapter, will prevent cold air from the outside from finding its way into the furnace. If “pocketing” is feared this may easily be overcome by providing some flue outlet on a level with the hearth, as in Fig. 101.

**Vents and Cold Streaks.**—The question of roof vents may also be approached from a different angle—that they will tend to set up a

current of cold air through the heating chamber. The natural tendency of roof vents is, as we have previously said, to short-circuit the hot gases through the roof. This means that there will be a pull or suction around the door towards the inside of the furnace, across the charge and thence to and out through the roof. Cold air, with free oxygen, will; therefore, be sucked into the furnace and will cause scaling, non-uniform heating and widely variant results. The further result of these vents is a loss of heat and destruction of the lining due to quick cooling after the burner has been shut off. This condition is emphasized by an unfortunately common type of heating furnace shown in Fig. 102; in this instance the heat is supplied from above the hearth, and by looking into a furnace of this type a dark streak of cold air will be seen to lay directly over the steel<sup>1</sup> on the hearth.

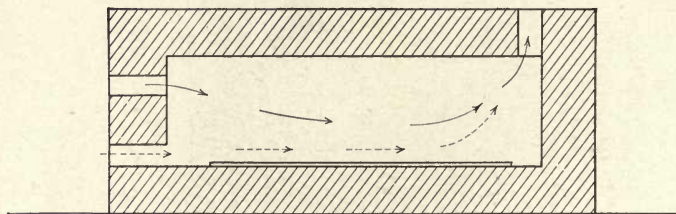


FIG. 102.

**Door Heights.**—It will also be noted that in Figs. 98 and 99 the height of the door opening is the same as the height of the roof arch; this is also objectionable practice under most circumstances. It is reasonable to assume that the height of the door opening is governed by the maximum height of the charge desired, plus a reasonable allowance to facilitate the handling of the material. If this is true, then it may be expected that the height of the charge may frequently reach almost to the roof. This condition will lead to localized heating at the top of the charge; and if there is an open vent in the roof such a condition will be magnified for reasons previously mentioned. It is, therefore, advisable to have the roof higher, as illustrated in Fig. 103, so that even with the maximum charge there will be ample space for the gases to become thoroughly equalized and to prevent the charge from encroaching upon the hotter zone close to the roof.

<sup>1</sup> This particular example is taken from a well-known spring shop.

**The Heat Reservoir.**—Further, when the door is opened in the furnace in Fig. 103, there is always a reservoir of heat left in the upper part of the furnace to aid in heating the next charge and maintaining the temperature of the furnace during discharging or recharging

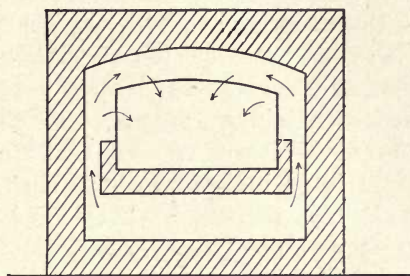


FIG. 103.

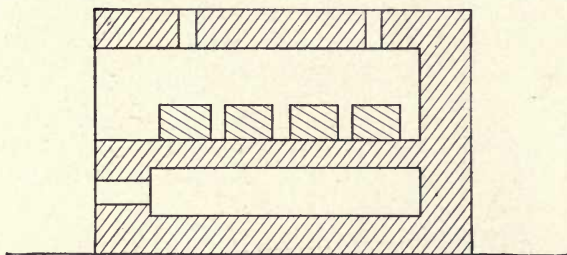


FIG. 104.

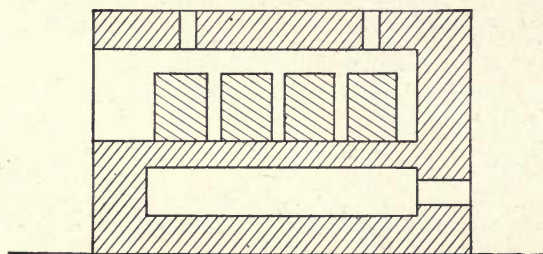


FIG. 105.

operations. With the furnaces in Figs. 98 and 99 this is impossible, for when the door is opened the furnace will be almost entirely emptied of its hot gases because the door opening is the same height as the roof. This is perhaps more clearly illustrated by the furnaces in Figs. 104 and 105. It is better practice to have the roof higher



than the door opening, and always to keep the door height as low as possible, as is illustrated by the furnace in Fig. 106.

**Height of Chamber vs. Height of Charge.**—In order to make quick use of the heat which is thus retained in the furnace, it is a part of the furnace man's job to provide for ample space for circulation throughout the mass. Thus with the charge arranged as in Fig. 104 there is ample room for the circulation of the hot gases around the charge, and the heat application would be much better and more uniform than in Fig. 105, where the top of the charge is near the roof. From this it will be seen that the size and arrangement of the charge is an indication of the heat application value of a furnace. Better results will be obtained in a high chamber with a low charge than if the charge is higher.

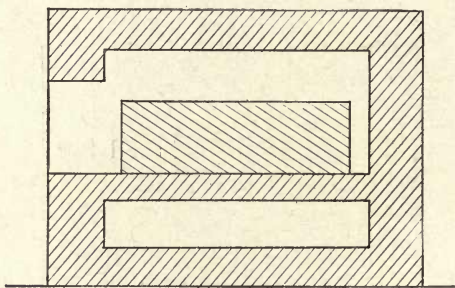


FIG. 106.

It is better practice to have the chamber high enough to afford plenty of space for circulation, as is illustrated in Fig. 106. This diagram also illustrates the points previously made concerning roof vents and door heights.

**Influence of Mass.**—The furnaces shown in Figs. 107 to 115 incl. illustrate different commercial methods for the pot annealing of wire, and are particularly *à propos* as examples of heat application on account of the size of the mass to be heated.

Thus in Fig. 107, we have a furnace with a combustion chamber under the hearth, and with a large pot resting directly upon the hearth. No matter how uniform the temperature may be in the chamber there will always be a tendency for a cold zone to form at the bottom of the pot—as is represented by the shaded portion in the drawing. This is due to the fact that the floor of the furnace is of a refractory nature, and will not transmit the heat as fast as the pot

will take it away. The placing of the pots in the furnaces in Figs. 109, 110 and 111 is better in this respect, inasmuch as it provides for the circulation of the hot gases under the pot.

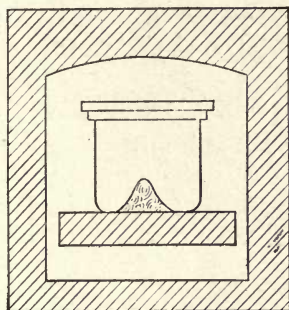


FIG. 107.

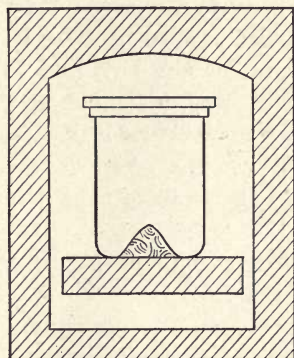


FIG. 108.

With a short pot, as in Fig. 107, it is sometimes permissible to use a furnace in which the heat is applied from the top of the charge downwards; but there is a limit to this because when the height of

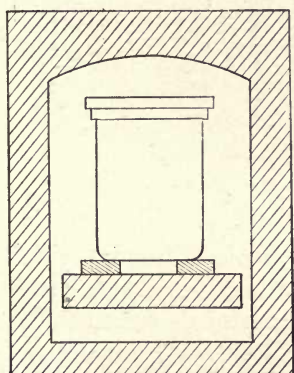


FIG. 109.

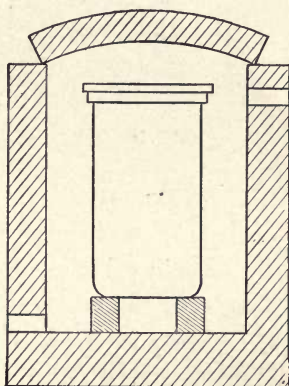


FIG. 110.

the pot increases, as with Figs. 108, 110 and 111, there will be a tendency to overheat the top of the pot before the bottom is at the right temperature. For this reason the height of the pot (or charge) in itself determines the type of furnace.

In some plants the heat is applied to the bottom (but without a separate combustion chamber) and taken off at the top, as in Fig. 110; but even with this construction it is difficult to secure a uniformly heated product, as the temperature of the top and bottom of the furnace rarely would be the same. In this respect the design of Fig. 111 is better. This latter provides for underfiring, for circulation under the pot, and further takes the gases off at the hearth (not shown), inasmuch as the heat must rise to the roof and return to the floor before it can escape.

When the construction in Fig. 110 (with a heavy roof-door) takes the form of that in Fig. 112 (with a cast-iron top), as it fre-

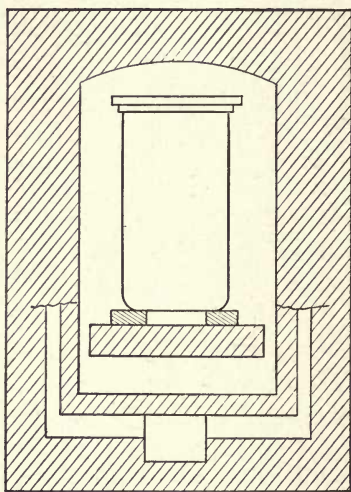


FIG. 111.

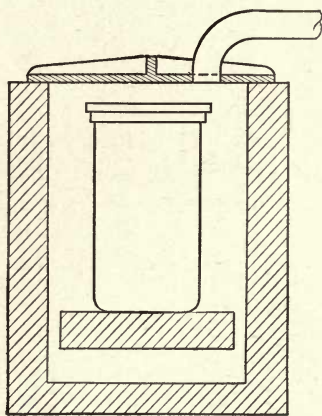


FIG. 112.

quently does in practice, the method is open to still more criticism. In either case the removal of the door, which constitutes the roof of the furnace, permits the escape of a maximum amount of heat and cools off the furnace. But in Fig. 112 the roof, being of metal, radiates a great amount of heat even with the top on the furnace, and is severe on the men. It is better practice to employ a type of furnace in which the charge is introduced through a door or opening in the side or end instead of through the top of the furnace.

Fig. 113 illustrates a construction of pot that is employed very successfully in annealing wire, and it gives very good results, inasmuch as the heat is applied to the center of the coils as well as the



outside, and to the bottom as well as the top. It goes to prove that the type of charge has much to do with uniform heating.

Figs. 114 and 115 illustrate the relative merits of heating high pots from the bottom up (Fig. 114) and from the top down (Fig. 115). In the underfired furnace, also provided with a movable ball type carriage or charging device, the heat is again first applied where it is most needed—at the bottom—and the hot gases rising will naturally take care of the heat application at the top. In the overfired furnace (Fig. 115) the gases must descend and even though

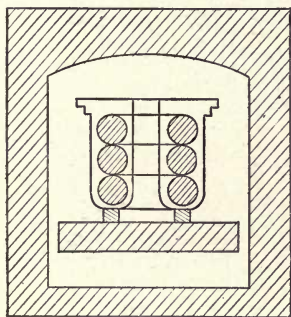


FIG. 113.

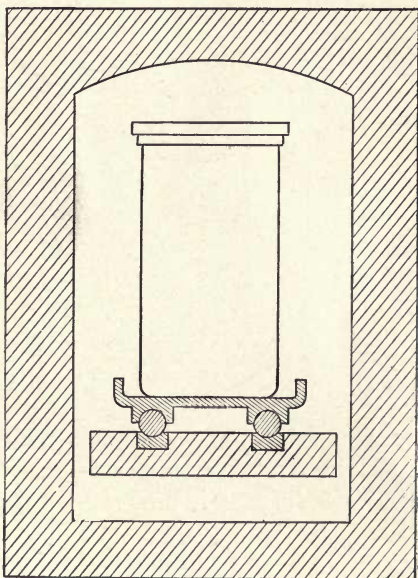


FIG. 114.

the heat is forced to circulate under the hearth, that part of the hearth under the charge will always be the cold spot, due to the fact that the absorptive powers of the iron pot is greater than the heat input of the hearth by the hot gases thereunder. The relative advantages of the two methods of heat application will be more fully discussed in subsequent sections, but it is here evident that the height of charge again determines the method of applying the heat.

**Influence of Character of the Charge.**—A charge in a furnace heats up in about the same manner as a plate of ice cream while melting—that is, from the top and outside edges towards the center—

particularly when the heat is applied from above. The difference between uniform chamber temperature and uniformly heated product is illustrated by Figs. 116 and 117, in which it is assumed that the

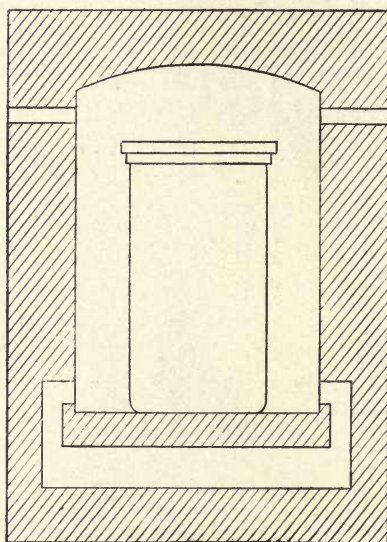


FIG. 115.

charge consists of small pieces—such as lock-washers or cartridge shells—laid on the chamber floor. It is immaterial in this case whether the furnace is underfired (Fig. 116) or overfired (Fig. 117),

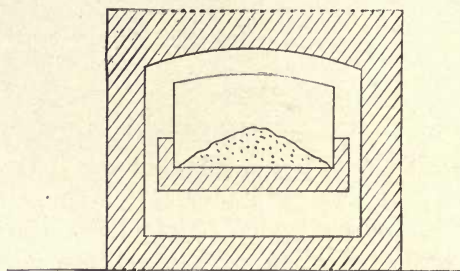


FIG. 116.

or how uniform the actual temperature in the chamber may be, because there will always be a tendency for a cool section in the center, as shown in Fig. 118. It is practically impossible to get a

uniformly heated product under such conditions unless the charge is so split up as to permit free circulation of heat through the mass. The real test in annealing, hardening or tempering is in the uniformity of cooling—that is to say, it is not only necessary that a piece should be uniformly heated, but it must also be uniformly cooled. For this reason, instead of heating small pieces as shown in Figs. 116 and 117, it is better practice to employ an automatic type of

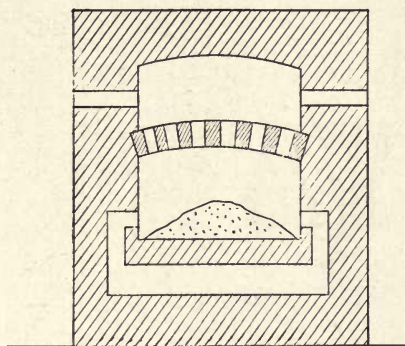


FIG. 117.

furnace like Figs. 119 or 121. With these designs each surface of each piece is exposed to the action of the heat, and it is heated and cooled uniformly. In other words, the material to be heated is indicative of the method of heat application and furnace design.

**Muffle Furnaces.**—Muffles, as ordinarily constructed for heat treatment work, do not necessarily prevent oxidation, other claims



FIG. 118.

to the contrary. The following are statements taken from recent publications on this subject: (a) "When oxidation or the formation of scale is particularly objectionable, furnaces of the muffle type are often used, having a refractory retort in which the steel is placed so as to exclude the products of combustion." (b) "The metal does not become saturated with any of the products of combustion . . .", referring to the furnace illustrated in Fig. 123.



The first statement, referring to the merits of the muffle versus the open chamber, must lead to the conclusion that muffles are synonymous with *improper* open chamber work. We have previously explained that, with proper furnace design and correct operation, an atmosphere may be produced which will contain no free oxygen,

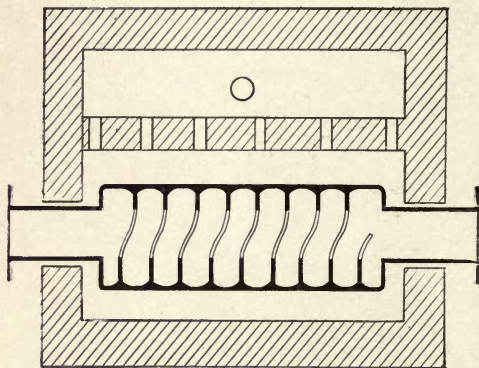


FIG. 119.

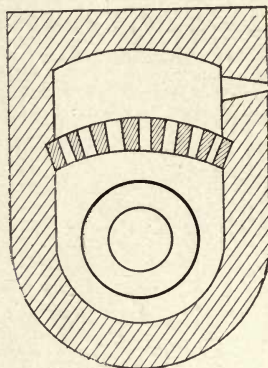


FIG. 120.

no oil vapors, and just enough carbon monoxide to take care of any air which may possibly find its way into the heating chamber through unforeseen causes; that this slightly hazy atmosphere results from an absolute control of the air supply, in combination with the right furnace design; and that a furnace operated in such a manner will

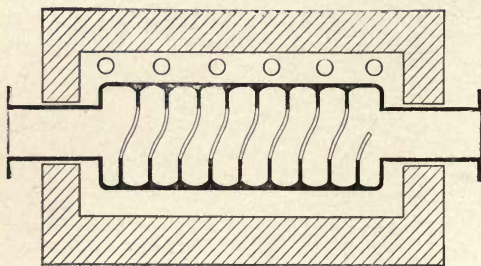


FIG. 121.

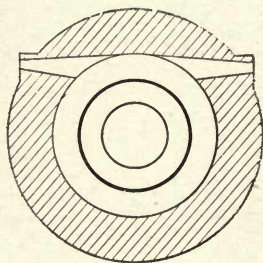


FIG. 122.

give a product which will often be better than that heated under charcoal. Thus when it is found necessary to exclude the products of combustion from contact with the hot steel, it means that such gases contain free oxygen, and which is identical with improper furnace operation or design.

Again, if the products of combustion are excluded from the muffle, the question reverts to the fact that there is no method of keeping the outside air or oxygen from finding its way into the muffle. As there is no pressure of gases from within, since the pressure which should be caused by the products of combustion is absent, the free oxygen must inevitably find its way into the muffle. For these reasons, therefore, muffles do not prevent oxidation.

**Semi-Muffle Furnaces.**—On the other hand, if a pressure is built up from within the muffle to prevent air from entering, there must be some opening between the muffle and the hot gas chamber surrounding it. In such a case it is no longer a true muffle and does not exclude the products of combustion. Thus in Fig. 123 there are

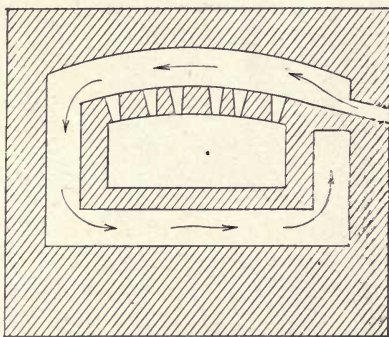


FIG. 123.

shown openings in the roof of the muffle. If the course of the hot gases is such that the gases come downwards through these openings, then why have any roof at all on the muffle?—for the products of combustion enter the heating chamber and the furnace approximates open chamber construction. Or, if the flow is upwards through these openings, then outside air will be sucked into and through the muffle, and oxidation will be set up in that manner. In other words, whether or not the furnace, as, and for the purpose designed, is properly operated, there is no occasion for the remaining solid part of the muffle roof, and the statement contradicts itself.

**Influence of Nature of Fuel on Furnace Design.**—The overfired, perforated-arch type of furnace—under which Fig. 123, previously discussed, may be classed, and which general type is common to the construction shown in Fig. 124—is a development originally intended

to meet certain conditions with oil fuel, but which is neither necessary nor desirable with gas or coal. The development also illustrates the difference between uniform application of heat and uniform application of fuel which was discussed in the last chapter (q.v.).

With a type of rotary annealing furnace like that in Figs. 121 and 122, using gas as a fuel, the burners are usually placed on both sides, so that a small amount of fuel is injected through each burner. This distributes the application of the fuel. With oil, however, the consumption under a similar arrangement of burners

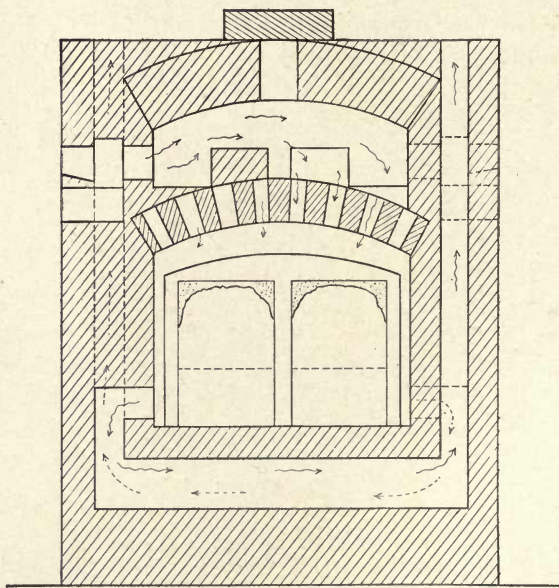


FIG. 124.

would be so low that the burners could not be kept going steadily, and for this reason it was desired to employ but one burner. This, in turn, was open to the objection that there would be a hot streak directly in front of the burner and which would react unfavorably on the charge. To overcome this the perforated arch was employed so as to lessen the streaking effect of the flame and thus distribute the heat, as is shown in Figs. 119 and 120.

It is therefore evident that the nature of the fuel in these cases determines the design of the furnace. In the first case (Figs. 121 and 122) the uniformity of heating, aside from the nature of the



charge, is secured by a uniform burning of the fuel—gas—throughout the length of the furnace. In the second case (Figs. 119 and 120) the fuel—oil—input is concentrated and the perforated arch construction is employed to secure the heat distribution. The perforated arch, which was found advisable in the case of oil, for the purpose in view, is entirely unnecessary with gas fuel.

Another illustration of this perforated-arch type as applied to a long, low hearth with concentrated

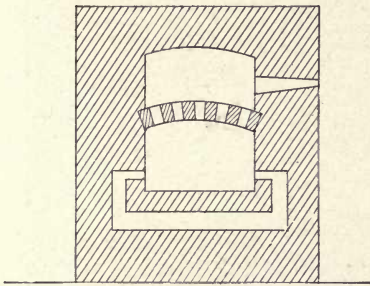


FIG. 125.

fuel supply, and which followed the above development, is shown in Figs. 125 and 126. In this case also the fuel input is from one side of the furnace and above the hearth; the perforated arch distributes the heat to the chamber beneath and from which the gases pass underneath the hearth. But it should be remembered that while the perforated arch construction may be perfectly proper under certain conditions, it may be entirely out of place under other conditions, and yet using the same fuel.

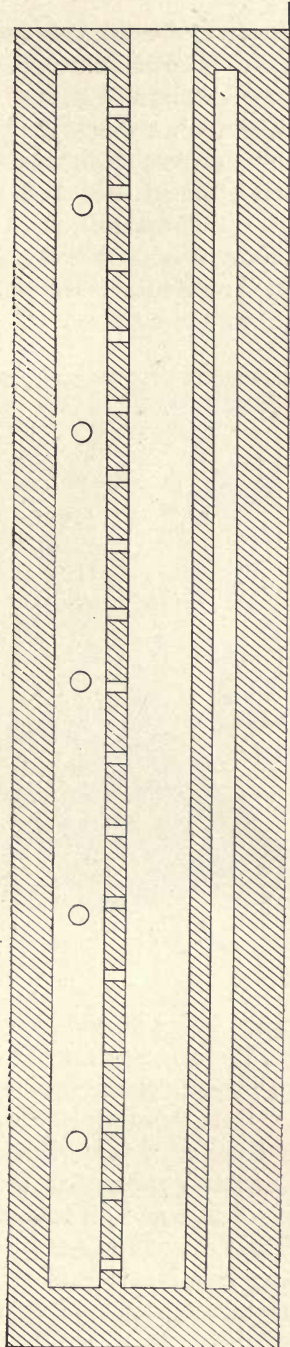


FIG. 126.

**Perforated-arch Furnaces.**—From the type of furnace of Figs. 125 and 126 it is but a short step to the overfired, perforated-arch furnace shown in Fig. 124 (previously alluded to), and which has been somewhat widely employed for general heat treatment work—often regardless of distinctive shop and heat application conditions. It will be noted that there are burners on both sides of the furnace (generally staggered), that the combustion takes place in a chamber above the main working chamber, and that the gases then pass down through the perforated arch into that chamber and are taken out from under the floor.

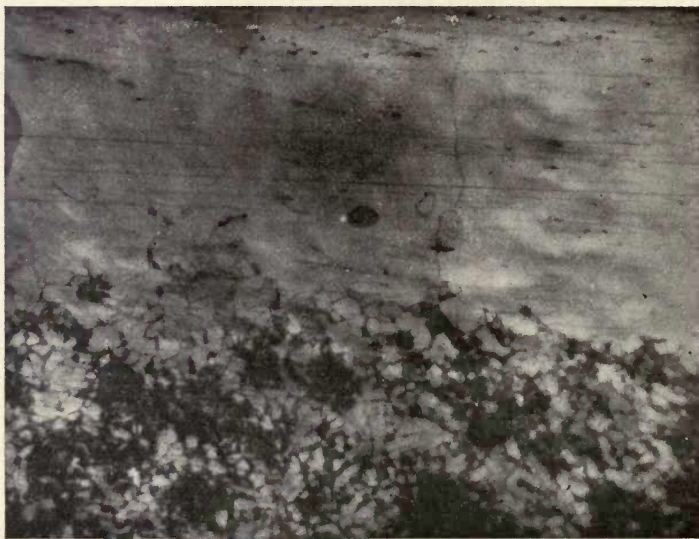


FIG. 127.—De-carburization of Steel by High-velocity Gases.  
×60. (Bullens.)

This design provides, in effect, for the application of heat from above through a perforated arch, and is permissible with low charges, but when the charges are high there is a tendency to overheat the top. If a thorough study is made of the perforated arch itself, it will be found that the actual openings only total about twenty-five or thirty per cent. of the total chamber area. With a continual input of fuel and air into the hot combustion chamber above, and with but a small exit for the hot gases, these hot gases must enter the working chamber at a high velocity. If the furnace is charged to anywhere near the height of the working opening or arch, which

is a common procedure, the hot gases will impinge upon the top of the charge at high velocity. This inevitably results in severe cutting action and oxidation, the zone of which is shown in the charge in Fig. 124. This is further illustrated by the photomicrograph of Fig. 127, taken from the edge of an annealing charge of chrome nickel steel plates piled as illustrated in Fig. 124. It will be seen that the steel has been entirely decarburized along one edge, even though the actual indicated temperature of the furnace was only about 1350° F. In the plant from which this example was taken it was no uncommon occurrence to lose as much as  $\frac{1}{4}$  or even  $\frac{1}{2}$  in. of metal on each side of a pile 10 or 12 in. wide.

Aside from changing the type design of the furnace, the only method of overcoming this particular trouble without decreasing the production is to increase the height of the working chamber. In this manner the gases are given an opportunity to expand before reaching the metal, and thus reduce the high velocity caused by the perforated arch. In other words, an overfired, perforated-arch furnace is permissible with low charges, in comparison with chamber height, such as is shown by the dotted line charge in Fig. 124.

**Overfired Furnaces.**—In order to overcome the necessity for comparatively high-working chambers, as occasioned by the conditions above referred to, the perforated-arch construction may be eliminated. This results in a type of overfired furnace illustrated in Fig. 128. In this case the charge is heated from the top downwards, and the gases pass out from under the floor. Aside from the fact that the hot gases have to pass downwards, the question then arises as to the manner in which the charge is heated. Since the heat is applied from above there is no question but that the top of the charge will be heated; but how about the bottom of the charge?

It should be borne in mind that this construction (with flues under the hearth) does not necessarily result in a hot floor, even though it be granted, for sake of argument, that there is a considerable volume of gases under the floor and that the temperature of these gases is the same as above the floor. The specific heat of the charge is such that it absorbs heat from the floor, and unless the rate of input is greater than the rate of absorption the floor will cool under the charge in proportion to the manner in which it is packed. This cold spot, in turn, means a cold zone through the center and bottom of the charge, and until this cold zone is removed the charge is not uniformly heated. But in order to remove it, it is necessary to



lengthen the time of exposure, which results in a tendency to expose the outside edges of the charge to the action of the heat and gases longer than is necessary with other construction. In practice this cold spot is never totally eliminated in this type of furnace.

Even with the I-bar floor construction illustrated in Fig. 128, which is the best in use for this type of furnace, the floor is not as hot as it should be. The reason for this is that, irrespective of the temperature or volume of heat under the floor, the rate of transmission of heat to the under side of the charge is no greater than that possible through the vertical section of the I-bar. The rate of transmission through the tiles separating the bars is still less than

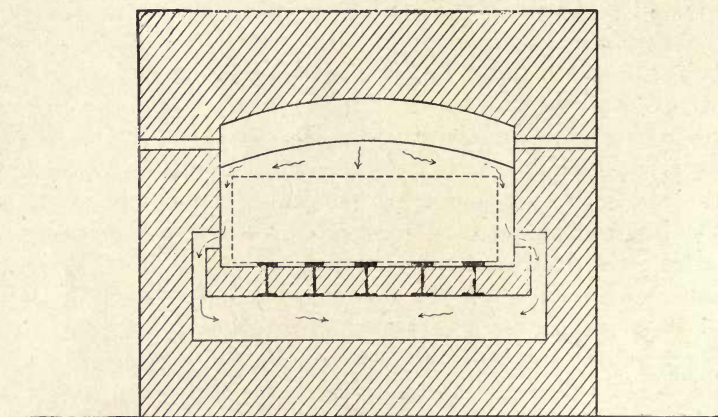


FIG. 128.

through the bars themselves on account of the low conductivity of the material. When the construction is made without the I-bars, as it sometimes is to lower the cost, the conditions are still worse.

From this it will be seen, as has been repeatedly proven in practice, that there is a disadvantage in any construction which does make possible a floor temperature equal to that above the charge; or a circulation of heat under the charge to make up the loss in transmission and decrease the time of exposure by decreasing the area of the cold zone.

**Influence of Arrangement of Charge.**—Such a condition just described illustrates very forcibly the difference in heat application obtained when a furnace is full and when it is empty. That a

furnace will give uniform temperatures without a charge is no criterion that the heat application to a charge will be uniform. The type of furnace illustrated in Figs. 129 to 134 is used extensively in the annealing of wire and tool steel, and many people wonder why it is that with almost perfect pyrometer records they do not get a uniform product.

The furnace is fired with coal from a fire-box at one end, the flame and heat passing over a bridge wall to the heating chamber; at the other end of the hearth the hot gases pass down and under the hearth through a series of flues, and from thence to the chimney. The hottest part of the hearth is near the bridge wall.

In the case of the charge of wire in Figs. 129 and 130 the non-uniformity of product is partly due to the fact that the first piece in is the last piece out and vice versa, so that the first piece is exposed to the highest temperature for the longest time, and the last piece to the lowest temperature for the shortest time.

With the method of charging tool steel in Figs. 131 and 132 the non-uniformity is partly due to the lack of circulation through the charge; the tubes rest directly upon the hearth and are packed tightly together. This can be somewhat overcome by rearranging the tubes as in Figs. 133 and 134, separating them and raising them up from the hearth.

All of these (Figs. 129-134) are open to the objection that the heat is not uniform throughout the length of the charge, and while it is possible to vary the quality of the product by rearranging the charge without affecting the pyrometer readings, as above illustrated, there is still the fact that the heat should be uniformly applied throughout the entire length and through the mass in order to secure a uniformly heated product.

This latter point is also illustrated by Figs. 135 and 136. In carburizing work the practice of Fig. 135 is often followed, filling the furnace to its maximum capacity by packing the boxes up to the side walls as well as in front. It is much better practice to maintain circulating space on the sides and ends, as shown by Fig. 136, and not to place the boxes beyond a certain imaginary line such as is illustrated by the dotted line of the drawing. The method of handling or arranging the charge in the furnace is equally important with correct furnace design and proper operation or heat distribution.

**Other Furnace Designs.**—The designs of furnaces intermediate between the two principal types—underfired and overfired—are legion. One characteristic furnace in common use is that illustrated

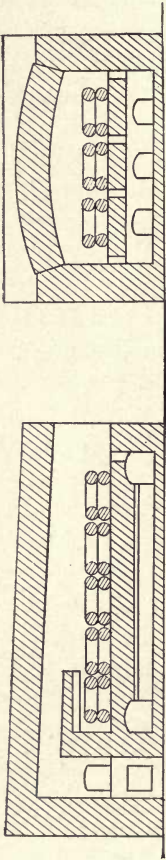


Fig. 130.

Fig. 129.

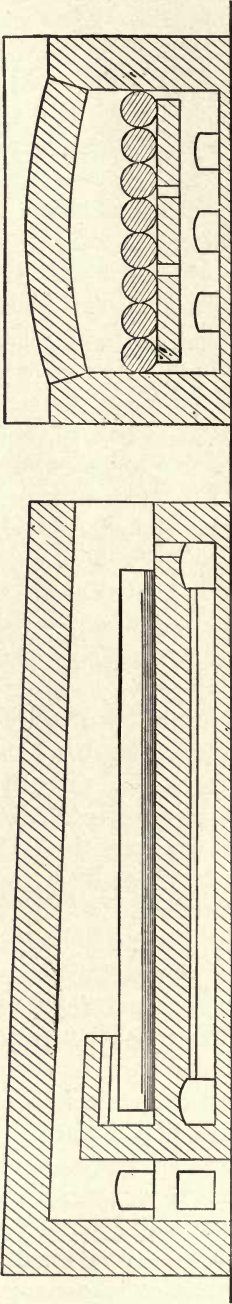


Fig. 132.

Fig. 131.

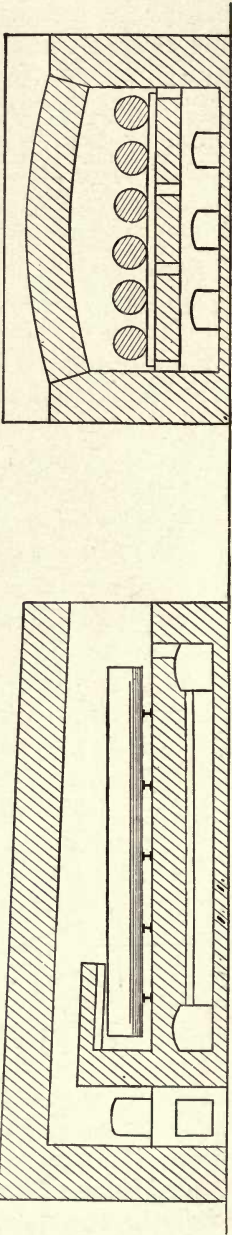


Fig. 134.

Fig. 133.



by Fig. 137. In this it will be noted that the underfiring principle has been used, locating the combustion chamber under the hearth; that the hot gases pass upwards to the heating chamber on *one*

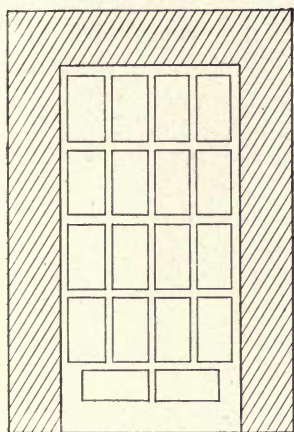


FIG. 135.

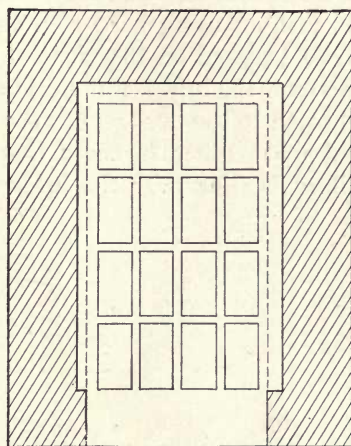


FIG. 136.

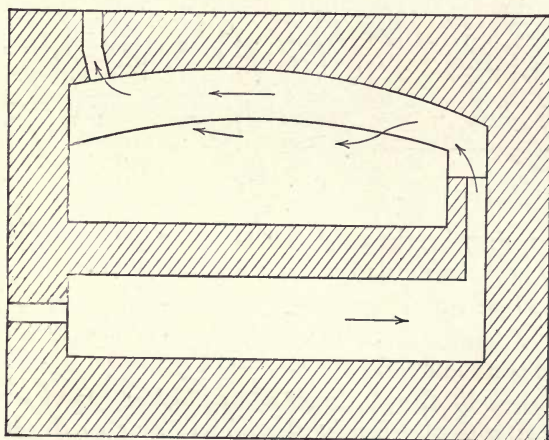


FIG. 137.

side of the hearth; and that a roof vent is located on the opposite side of the chamber. In this design the benefit of underfiring is largely negated by the poor heat application to that part of the charge and hearth directly under the vent and farthest removed

from the heating chamber intake ports; the hot gas currents will short-circuit from the ports to the vent. A good overfired furnace would be better practice.

**Coal Furnaces.**—Fig. 138 illustrates a common type of heat treatment furnace using hard coal as the fuel. The heat is generated from coal placed on the grate at the left of the furnace illustrated, passes over the bridge wall into the heating chamber, and then under the hearth to the flues and to the chimney. From points previously raised upon other furnaces there will be noted the tendency to localized heating near the bridge wall, the fact that the height of

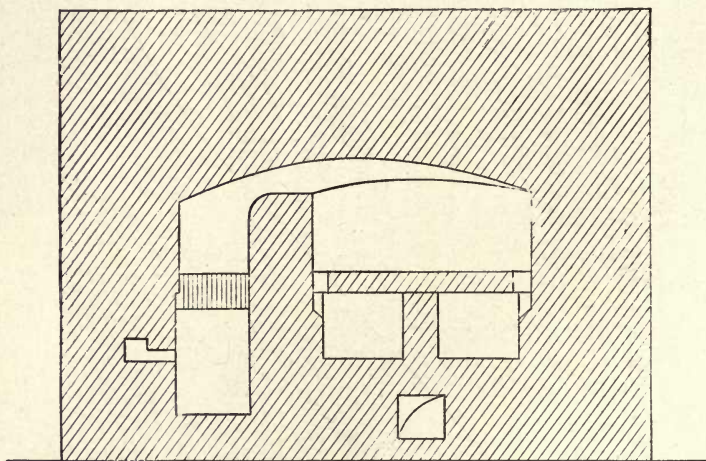


FIG. 138.

the door opening is virtually the same as that of the roof arch, and the tendency towards a cold hearth. In such coal furnaces as generally designed and operated there is a decided lack of control of the volume, temperature and composition of the gases to and from all points in the chamber.

Again, when local conditions advocate the use of a cheap fuel, such as coal (and why use hard coal at \$7 or so a ton when soft coal at \$2 a ton could be made to do the same work?), the general method of burning it, as here illustrated, is found to be inefficient from the standpoint of fuel application and unsatisfactory from the heat application viewpoint. The only proper way to attack such a problem is first to gasify the coal and properly to utilize that gas; not necessarily to generate the gas in a separate producer

and carry it by expensive flues to the furnace, but to combine the two operations in one efficient, self-contained unit. Such is being done, and such furnaces are today producing a better heated product, at less operating cost, than many furnaces using oil or gas.

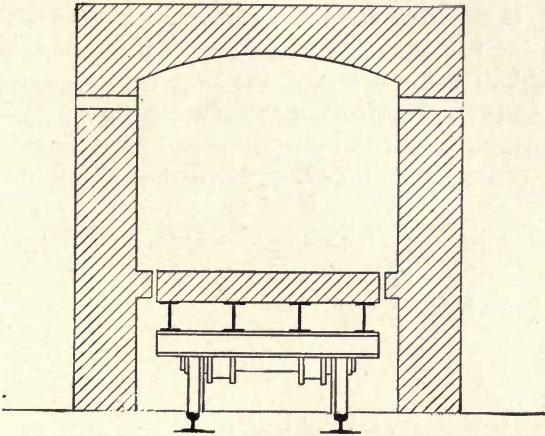


FIG. 139.

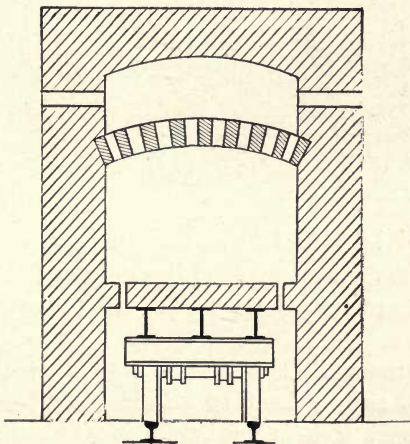


FIG. 140.

**Car-bottoms.**—Figs. 139, 140 and 141 represent three designs of the car type furnace—the open-chamber, perforated-arch and coal-fired furnaces respectively.

Furnaces with the movable car-bottom may be mechanically



efficient, but they are thermally inefficient. In cases where there is much work to be handled of a large and variable size, the use of such furnaces may be advisable. But it is the same proposition of cold hearths versus hot hearths which has been previously discussed, but carries the matter one step farther. In this case, each time the hot car is removed from the furnace a large amount of heat is lost, and the furnace must be refired with a cold hearth. Similarly, the radiation losses during the time between the removal of one charge and the placement of the new car are very great. However, the saving effected in both labor and time may be considerable under certain conditions as above noted, but in any event

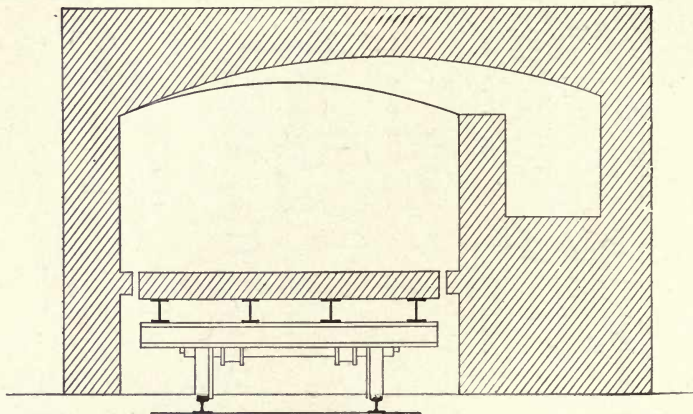


FIG. 141.

the charge should be raised from off the hearth to give the best circulation possible. Furnaces with car-bottoms should only be used when there are no others which will prove as commercially effective.

**Underfired Furnaces.**—The aim of any uniform heating operation should be to supply heat to all sides of the charge. Under ordinary conditions, this is probably most nearly accomplished in the underfired type of furnace with a perforated floor, and an effort has been made to overcome the disadvantages previously referred to in the discussion of other types of furnaces. Fig. 142 illustrates a recent patented type of underfired furnace, and comparison should be made with the overfired furnaces previously described, such as in Fig. 128.

The heating is done from the bottom upwards instead of from the top downwards. Heat naturally rises, and with such construction as in Fig. 142, if the floor is hot the roof is hot, although it is possible to obtain the reverse in an overfired furnace. Even in an underfired furnace the bottom can never be heated more than the top. In the construction outlined in the drawing, the gases are passed through large combustion chambers and compelled to circulate through several hundred feet of ports on both sides, as well as through the floor, each of which exposes considerable area

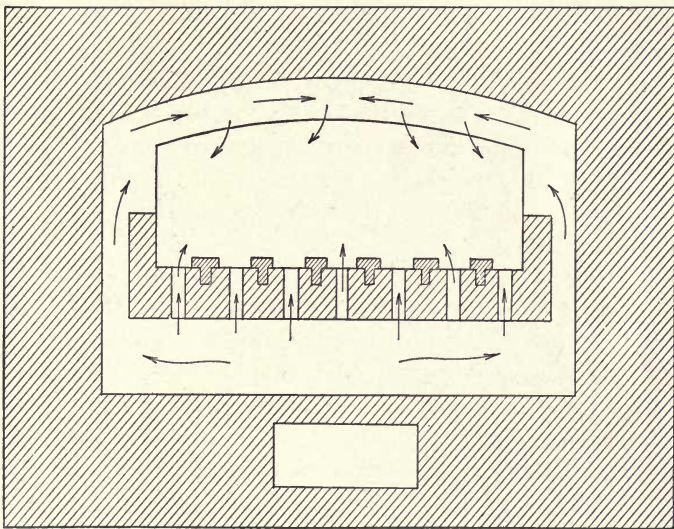


FIG. 142.

against which the gases are wiped. In this way there is a minute subdivision of the volume and a thorough mixture.

Such a furnace design is also in accord with the fact that correct heating is a function of pressure. Thus the heat, in going to the roof, naturally stratifies and builds up a natural pressure, which will be spread over the entire area before it will come down. The result is a pressure always on the floor and the elimination of streams of gases of unequal temperature and composition. The hot gases surround the steel as a blanket, and have a minimum velocity. With such methods of applying the heat, the area of the cold zone is quickly decreased, and this, in turn, lessens the length of exposure.

It will also be noted that provision is made for circulation on

both sides of the charge, independent of the manner in which it is packed. It is impossible to overload the furnace and cut off the circulation, and even though the charge were the full width and height of the working opening there would still be room on each side for circulation. In the particular furnace illustrated, this extra room costs about three feet in chamber width; the area for circulation on the sides is about 30 per cent. of the width of door, and it is by the room afforded with such greater width that the velocity of the gases is cut down.

On the other hand, and in the case of the overfired furnace of Fig. 128, it will be noted that if the chamber is the same width as the working opening, it will be necessary to employ comparatively small charges in order to get circulation through the restricted areas on the sides. To gain time, with this practice there is a danger of overheating for the reason that, as the area is decreased, the pressure must be increased for a given B.T.U. input, which works out in practice, as a rule, to the detriment of the top and exposed edges of the charge.

**Flue Construction.**—For furnaces of any considerable size, flue construction is absolutely necessary, not only to provide an escape for the waste gases, but also to direct the hot gas currents during their passage through the furnace, and to conserve the heat in those gases after they have left the heating chamber proper. Primarily, the practice is to circulate the gases around the stock to be heated, to heat the chamber as a whole, and then to pass them out at the coldest part of the furnace. Some of the furnace drawings given have shown in some degree such provisions, but in order not to complicate the discussion of heat application, the subject of heat conservation has been little dwelt upon. The latter is, in fact, a problem which must be studied out for each particular design. In any case the flues should be arranged so as to prevent short-circuiting of the hot gas cycle.

**Conservation of Heat.**—Additional flue construction and thicker walls both tend towards the conservation of waste heat. The discussion thus far has had to do with single furnaces, and the extent to which the thickness of the walls might be increased is obviously restricted within narrow limits by the cost of construction. Since losses by radiation are largely preventive, any arrangement or grouping together of furnaces of a similar type which will tend to unite them, thus eliminating exposed walls, should be made a subject of study.



**Variety of Furnace Plans.**—The diagrams in Figs. 143, 144 and 145 are intended to illustrate as floor plans a few of the many different

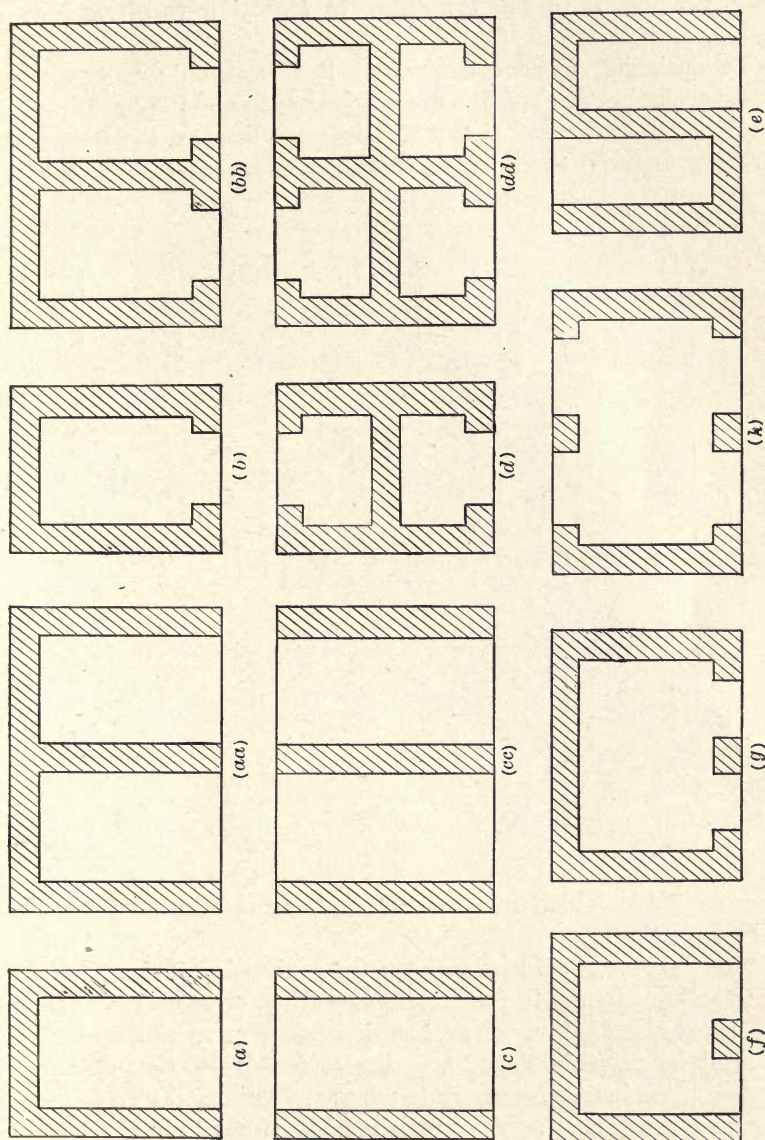


FIG. 143.—Furnace Plan Lay-Outs.

furnace designs which are employed in practice. All of these, which are more or less empirical, as well as hundreds of others not shown,

have been built in a variety of sizes for oil, gas, coal, coke and wood, with different methods of applying the heat to suit different operations ranging from small needles to eighty tons of steel at a charge.

In designing furnace equipment it is not only necessary to consider combustion and the more important points of heat application as well as the fuel suited to both, but likewise the method of handling material to and from the furnace, together with the floor

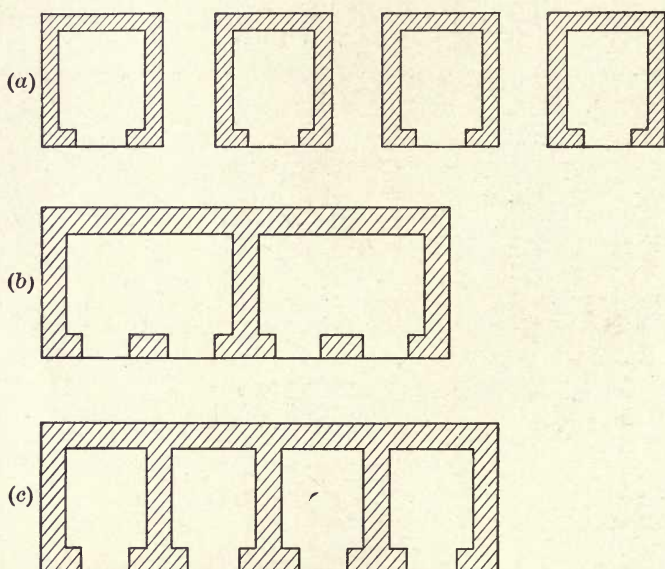


FIG. 144.—Unit Furnace System Development.

space available, which are no small factors in the cost of production and installation.

The purpose should be to keep the material, the men, the furnaces and machinery in continuous operation, or as near it as possible, because each is more or less dependent upon the others and all must be properly linked together to secure the best all-around results. It is just as necessary to adapt the furnace design to manufacturing conditions as it is with machine tools, but the latitude for variation is much greater.

Owing to the great variety of heating operations and shop conditions, it is rarely found that the same identical furnace can be

properly employed in two shops, or even in separate departments of the same shop, for similar operations.

Thus these sketches will serve to illustrate some of the development that has been made, as well as the latitude possible in designing furnace equipment, and further shows that furnaces cannot well be standardized owing to the great variety of conditions which must be met.

**Unit Furnace System.**—Every large factory employing heat treatment methods is more or less confined to a general type of product which requires some particular and standardized treatment. Such conditions would seem to be naturally and readily adapted to the small-furnace unit practice, having elasticity of production as its general aim. Thus it is no unusual sight to see ten or fifteen small furnaces, often on legs, of similar type and size, strung out in a row. And yet if the manager of that plant were to

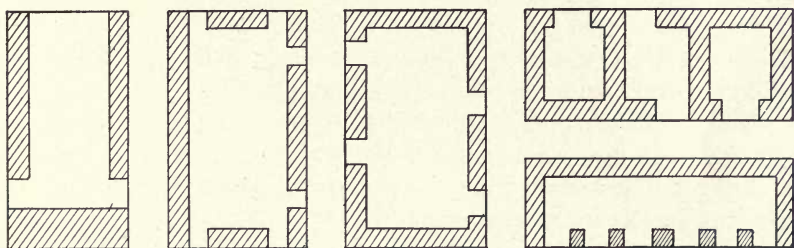


FIG. 145.

visit a boiler room where each of ten or more boilers were each set off by itself, how caustic would be his comments. The same principles of heat generation, utilization and conservation are applicable to both. Not only does the unit system of furnace arrangement require, as a general rule, more care and attention, involve more steps for the furnace man, longer time for heating and general inefficient handling, but it also tends to raise the cost of fuel out of all proportion to the product turned out. Radiation losses are largely responsible for this last cost factor.

Experience has shown that three, or perhaps four, small single furnaces of the same type for the same work, are about the general economic limit of the small-furnace unit system.

To explain some of the diagrams in Figs. 143, 144 and 145,



previously referred to, and to develop the growth of the multiple furnace, we might commence with *a*, *b* and *c* of Fig. 143.

In (*a*) the door opening is the full width of the chamber, giving opportunity for packing the charge to the full width of the opening; such a condition, as previously explained, is usually not advisable, as it tends to cut off circulation. It may be remedied as in (*b*), by placing jambs on each side of the front.

In (*c*) there is an opening at each end of the furnace, allowing for charging at one end and discharging at the other, or for working the same operation from both ends simultaneously. Such construction is thermally bad in that it permits a direct draft from one door to the other, with consequent loss of heat. If it were a question of doing the same work from each side at the same time, the layout might be changed as in (*d*) or (*e*) to prevent the cold air draft. Or if it were a matter of charging and discharging simultaneously without interference, the design might better take the form of (*f*), having the two openings at one end, and widening the furnace to make up for loss in length. In the latter construction the door openings could be smaller, and one side could be worked out while the other side was being charged and heated.

**Twin Chambers.**—The next logical step in avoiding the small unit system is to use twin chamber construction. For each exposed wall of the unit system which is removed, the more can we increase the sturdiness of construction, and there diminish the heat radiation loss of the remaining walls without additional construction cost. Thus the development of two furnaces of the (*a*), (*b*), (*c*) or (*d*) type, Fig. 143, will be that as shown in (*aa*), (*bb*), (*cc*) and (*dd*). Such furnaces will have the advantages of better heat application and conservation, and perhaps of handling material, but will have the disadvantage that if one side "goes down," the other will usually have to go out of commission also.

In some cases the dividing wall may be omitted as in (*g*) and (*h*), giving one large hearth. But in this case only one temperature work can be done at one time in place of the two temperatures possible in the twin chamber construction.

**Furnace Batteries.**—There are many plants which use small, light furnaces, built on legs which might advantageously combine the smaller units into batteries and obtain both better heat application and handling methods. Other things being equal, the construction and arrangement of Fig. 144 (*b*) and (*c*) would be much better than that of (*a*).

Other designs as necessitated by definite conditions of material handling or shop efficiency are illustrated in Fig. 145, and may be varied, of course, *ad libitum*.

**General Furnace Considerations.**—Full data should be gathered as to the sizes, shapes and approximate output, both maximum and minimum, of the material to be handled, besides the specific treatment desired.

Careful consideration should then be given as to whether or not the operations can be made mechanical, i.e., automatic or semi-automatic, or continuous. From this information the specific dimensions of the furnace can be deduced. As a general principle, it may be stated that the heating chamber should be large, but with a minimum area of exposure or door opening.

The furnace should be of the best possible design to suit the particular work in hand and under the certain existing factory conditions. The specific purpose for which the furnace is to be used should be definitely decided—whether for annealing, hardening, toughening, carburizing, etc., or for a combination of such operations. In this connection it may be said that the maximum efficiency of any heat treatment operation or furnace is obtained by using a furnace operating continuously on one class of work at one temperature and especially designed for that purpose.

Much thought should be given to the layout efficiency. The furnaces should be so arranged and such methods devised, that the material may be heated and handled with the least labor and loss of time.

**Practical Notes.**—In concluding the discussion of heat application, the author would ask for a thoughtful consideration of the following additional suggestions on heating:

(1) The rate of heat absorption by the object, under the regular methods of packing and furnace operation, should be obtained. The furnace man should know exactly the length of time it takes thoroughly to saturate that piece of steel under definite working conditions, and with the furnace maintained at the desired temperature.

(2) A furnace should always be maintained at one temperature, not permitting the indicated temperature in the furnace to go higher than that desired in the finished product. Forcing the furnace after each discharge is bad practice, and tends to place too much confidence in the weak link—the human element.

(3) The pyrometer and the time clock should go together.



(4) Heating and handling methods should tend to the principle of putting a cold piece in when a hot piece is taken out; of heating small units at one time (not meaning small furnaces, but units of charge) rather than increasing the mass; of giving the last piece in the same amount of heat as the first piece.

(5) There is no one fuel, furnace, or any other "one" which will satisfy every condition.



## CHAPTER X

### CARBON STEELS

**Foreword.**—In this and in the following chapters on various steels it is the author's intention to give the physical results which are representative of the different steels and their treatment. Such results have been gathered from practical work and experiment, and although the results of various treatments will vary according to the individual steel and the personal equation of the operator, they may be considered as fairly representative of the steel and treatments given.

Further, it must be remembered that the size of section or mass of the steel has a very important influence upon the physical test results. The same results will not be obtained in a steel bar of 4 ins. diameter as in a bar of the same steel with similar treatment and of only  $1\frac{1}{2}$  ins. diameter. Similarly, different results will be obtained near the outer surface of a large forging in comparison with a test taken near the center.

As an example of the effect of the size of piece upon the tensile strength, under the same treatment, we may cite the following examples:

Diameter of Bar Inches.	Tensile Strength. Lbs. per Sq. In.
$\frac{1}{2}$	137,000
1	132,000
$1\frac{1}{2}$	127,000
2	122,000
$2\frac{1}{2}$	113,000
3	105,000
$3\frac{1}{2}$	100,000

**Hardness vs. Maximum Strength.**—The following equations connecting maximum strength, Brinell hardness number and scleroscope hardness number have been computed <sup>1</sup> from several hundred

<sup>1</sup> R. R. Abbott, A. S. T. M., Vol. XV, Part II, 1915, p. 43 et seq.

tests made with carbon steels of different carbon content and heat treated to bring out all possible physical properties:

$$(1) M = 0.73 B - 28.$$

$$(2) M = 4.4 S - 28.$$

$$(3) B = 5.6 S + 14.$$

$M$  = maximum strength in units of 1000 lbs. per sq. in.

$B$  = the Brinell hardness number.

$S$  = the scleroscope hardness number.

The maximum strength corresponding to different Brinell values as determined by equation (1) for carbon steels is as follows:

Brinell.	Maximum Strength, Lbs. per Sq. In.	Brinell.	Maximum Strength, Lbs. per Sq. In.
100	45,000	350	227,000
150	81,000	400	264,000
200	118,000	450	300,000
250	154,000	500	337,000
300	191,000	550	373,000

The maximum strength corresponding to different scleroscope values as determined by equation (2), and the corresponding Brinell numbers as determined by equation (3), for carbon steels, are as follows:

Scleroscope.	Maximum Strength, Lbs. per Sq. In.	Brinell.
20	60,000	126
30	104,000	182
40	148,000	238
50	192,000	294
60	236,000	350
70	280,000	406
80	324,000	462
90	368,000	518
100	412,000	574

#### VERY LOW CARBON STEELS: UNDER 0.15 CARBON

The "dead soft" steels, about 0.10 per cent. carbon, find but little application to heat-treatment purposes. Contrary to general opinion, these steels *do* respond to heat treatment, although, of course, to a very limited extent. The best treatment to which these steels can be subjected is a quenching from about 1550° to 1600° F.,

with or without reheating, the reheating being omitted when conditions (of strain caused by quenching) will permit. Such a treatment will refine the grain and remove any strains set up by previous working; will confer added toughness; and will put the steel in the best condition for machining. This last is an important point, for this very low carbon steel, without high manganese and phosphorus, and in either the annealed or toughened condition, often does not machine freely, but is apt to tear badly in threading and turning operations. The heat treatment of very low carbon steel as applied to the wire industry is discussed in a subsequent chapter.

**Annealed.**—For annealing 0.1 per cent. steel, heat as rapidly as consistent with the size and shape of the piece to a temperature slightly above the upper critical range of the steel, approximately 1600° F. In these very low carbon steels the change into austenite takes place very rapidly, so that it is only necessary to allow the heat to penetrate the steel at the temperature noted above. As the grain begins to coarsen rapidly with increase in temperature and length of time held there, care should be taken in not overheating nor maintaining the annealing temperature for too long a time. Cooling may be carried out comparatively rapidly without danger of hardening the steel. The annealing of these very low carbon steels is usually for the purpose of relieving such strains as may be incurred by cold crystallization or by previous heating at a low-red heat for any great length of time.

**Heat Treated.**—The results obtained from the treatment of test bars  $\frac{3}{8}$  ins. in thickness of acid open-hearth steel of the composition:

	Per Cent.
Carbon.....	0.10
Manganese.....	0.32
Phosphorus.....	0.028
Sulphur.....	0.024
Silicon.....	0.019

are given in the following table:

Steel.	Tensile Strength. Lbs. per Sq. In.	Elastic Limit Lbs. per Sq. In.	Elongation. Per Cent. in 8 Ins.	Reduction of Area. Per Cent.
As rolled.....	51,625	35,500	34.5	65.3
Annealed.....	48,800	31,770	37.5	67.5
Water quenched from 1575° F..	64,720	45,550	22.8	61.15
1575° F. Water/1300° F.....	53,055	36,500	35.35	66.05



## GENERAL SPECIFICATION, ANNEALED

Tensile Strength. Lbs. per Sq. In.	Elastic Limit. Lbs. per Sq. In.	Elongation. Per Cent. in 2 Ins.	Reduction of Area. Per Cent.
45,000 to 55,000	28,000 to 36,000	40 to 30	65 to 55

## 0.15-0.25 CARBON STEEL

This grade of straight carbon steel is generally known to the trade as "machinery steel," and as such has innumerable uses where strength is not an all-important factor. The steel forges and machines well. The lower carbons find their greatest application in the case-hardening processes which have been previously described. The higher carbons are used considerably in certain engine forgings such as tie rods, valve stems, nuts, flanges, pins, levers, etc.; for machine work of various description; for structural purposes in automobile construction, etc.

**Heat Treated.**—Heat treatment of the lower carbons of this range confers but little additional strength except in thin sections, but does have a most desirable influence in the refinement of grain after forging or other elaboration. Hardening should be done from a temperature exceeding the upper critical range—which is about 1550° F. for 0.15 per cent. carbon, and about 1525° F. for 0.20 per cent. carbon—in order to effect the full absorption and diffusion of the excess ferrite. Some engineers recommend quenching at 1650° F. or even higher, but the author believes that such high temperatures are not only detrimental on account of a greater tendency to warping, oxidation and higher cost of treatment, but are also unnecessary metallurgically. In other words, those temperatures should be used which will produce the most efficient combination of physical properties, refinement of grain and low cost of production. From the results of extensive research work upon 0.18 to 0.28 carbon stock used for automobile purposes, and from a study of its working out in practice, the author recommends a quenching temperature of about 1500° to 1525° F. for these steels. Temperatures lower than 1500° do not bring out the full effect of the treatment, as is shown by the following average results (from a large number of tests) upon the same steel;

Quenched in Oil from—° F.; Re- heated to 800° F.	Tensile Strength. Lbs. per Sq. In.	Elastic Limit. Lbs. per Sq. In.	Elongation. Per Cent in 2 Ins.	Reduction of Area. Per Cent.
1450	70,220	43,460	24.1	48.4
1500	79,590	52,500	25.6	52.6

With hardening temperatures higher than 1550° F. there is practically no increase in the physical properties worthy of mention, and, moreover, the structure then begins to coarsen rapidly. The microscope <sup>1</sup> shows little or none of the original structure when the steel has been quenched from about 1500° to 1525° F.

With carbons greater than 0.18 or 0.20 per cent., and particularly if the section is small, or the manganese content is more than 0.60 per cent., the necessity of reheating or toughening after quenching becomes apparent. Hardening *small sections*, such as are used in automobile construction, from about 1525° F. without subsequent drawing—especially if water has been used as the cooling medium—will produce an *inherently* brittle steel. The physical characteristics under these conditions will be approximately as follows:

Tensile strength, lbs. per sq. in.....	90,000 to 110,000
Elastic limit, lbs. per sq. in.....	60,000 to 75,000
Elongation, per cent. in 2 ins.....	17 to 12
Reduction of area, per cent.....	30 to 15

By reheating to 800° or 900° F. a considerable increase in toughness and ductility is obtained, approximating:

Tensile strength, lbs. per sq. in.....	70,000 to 85,000
Elastic limit, lbs. per sq. in.....	45,000 to 60,000
Elongation, per cent. in 2 ins.....	35 to 20
Reduction of area, per cent.....	65 to 45

Cold-rolled material, subsequently given the same heat treatment as hot-rolled material of the same chemical composition, will usually show about 8000 to 10,000 lbs. per square inch higher in elastic limit and tensile strength.

Characteristic results from commercial work are given in the following table:

<sup>1</sup> See also page 44.

Material.	Carbon.	Mang.	Quenched in Oil from °F.	Re- heated to °F.	Tensile Strength. Lbs. per Sq. in.	Elastic Limit. Lbs. per Sq. in.	Elong- ation. Per Cent in 2 in.	Reduc- tion of Area. Per Cent.
General char- . . . . . acteristics	0.18 to 0.25	0.40 to 0.80	1500 to 1550	800 to 900	70,000 to 85,000	45,000 to 60,000	35 to 25	65 to 45
Auto. lever . . . . .	0.18	0.40	1650	800	70,030	45,400	32	64
Pressed auto. frame.	0.22	0.40	1530	800	71,950	43,400	29	56
Engine forging . . . . .	0.26	0.28	1650	1025	77,210	52,200	28	65
Old rolled $\frac{1}{4}$ in. plate	0.24	0.60	1525	900	93,300	65,250	20.5	51

The above remarks apply mainly to the smaller sections up to 2 ins. in thickness, but are nevertheless applicable in part to heavy work. With the increase in sectional area, the effect of hardening decreases, and for particularly heavy work may result only in a refinement of grain. Thus, for heavy, oil-treated forgings, toughening may not be considered a necessity; such reheating will, however, relieve the strains which are always inherent to quenched steels. Large forgings thus treated will show an elastic limit of 30,000 to 50,000 lbs. per square inch, with an elongation of 35 to 25 per cent. in 2 ins.

**Annealed.**—There is probably more disagreement and argument as to the proper annealing temperatures for this range of carbon steel than for any other. Opinion and practice are divided over the use of a comparatively high temperature—50° to 100° over the upper critical range—or a lower temperature laying somewhere between the Ac1 and Ac3 ranges. In this group the Ac1 and Ac3 ranges are widely separated and the influence of the carbon-manganese content is rapidly increasing. The high annealing temperature, 1550° to 1600° F. or more, will give ample opportunity for the absorption of the excess ferrite, for diffusion and for equalization. On the other hand, there is according to some authorities a marked increase in grain size from 1350° or 1375° F. and upwards.

The whole question really depends upon the condition of the steel before annealing. If the “breaking-down” during elaboration—either rolling or forging—has been severe, if high temperatures have been used, and if the finishing temperature has not been just right, a high annealing temperature may be necessary to entirely relieve the strains and equalize the steel. On the other hand, if the steel



has been carefully worked and the micrographic structure is fairly good, the lower temperatures will probably be entirely satisfactory. Much must be left to the operator and his own particular problem. The main point to bear in mind is that the lowest temperature should be used which will produce the desired results.

If we assume as average figures for annealed steel of this carbon range:

Tensile strength, lbs. per sq. in. . . . . 58,000 to 65,000

Elastic limit, lbs. per sq. in. . . . . 28,000 to 35,000

Elongation in 2 ins., per cent. . . . . over 30

and compare these with the results of a tensile test taken from the steel to be annealed, a very good idea of the degree and length of heating may be obtained. For example, the following results from 1½-in. rounds for gun barrels show that a high annealing temperature was not necessary in this case, inasmuch as the original steel was in excellent condition.

Gun barrel steel, 1½-in. rounds.

Carbon, 0.18 per cent.

Manganese, 0.50 per cent.

Phosphorus, 0.070 per cent.

Sulphur, 0.055 per cent.

Silicon, 0.055 per cent.

Treatment.		Tensile Strength. Lbs. per Sq. In.	Elastic Limit. Lbs. per Sq. In.	Elongation. Per Cent. In 3 Ins.	Reduction of Area. Per Cent.
As Rolled		66,750	33,820	33.3	57.6
Annealed at					
degrees F.	for minutes				
1360-1400	30	64,960	34,050	38.0	61.0
1500	20	65,180	32,930	38.3	58.3
1500	105	64,060	33,150	39.1	62.3
1830	15	62,940	31,810	35.7	56.3
2120	5	61,150	31,580	33.8	53.1

On the other hand, the following cold-rolled automobile-frame steel was particularly "hard" before annealing and required a temperature of 1550° F. to relieve thoroughly the effect of the cold work:

Carbon, 0.24 per cent.

Manganese, 0.38 per cent.

Phosphorus, 0.028 per cent.

Sulphur, 0.038 per cent.

	Tensile Strength. Lbs. per Sq. In.	Elastic Limit. Lbs. per Sq. In.	Elongation. Per Cent. in 2 Ins.
Before annealing . . . . .	100,400	68,500	18.6
After annealing at 1550° F. . . . .	66,000	38,100	37.0

For the *average* run of annealing work for this range of carbon, a temperature of about 1500° F. will be found to give satisfactory results; individual cases must be treated as such.

#### 0.25-0.35 CARBON STEEL

Steel containing from 0.25 to 0.35 per cent. carbon is known as soft-forging steel and is used principally for structural purposes in infinite variety. It responds in a most satisfactory manner to welding, forging and machining, and may be vastly improved by proper heat treatment. Under skillful treatment, the variety of combinations of strength and ductility are to be had in probably no other range of carbons.

Relative to static strength, some really wonderful results—for straight carbon steels—in the way of high tensile strength with high ductility have been obtained from heat-treated (oil quenched and toughened) forgings of 0.30 to 0.35 per cent. carbon. The following results, obtained from the center of a 5-in. electric car, heat-treated axle, the axle being selected at random from a group of about one hundred forgings, give an idea of the extent to which proper heat treatment may develop the physical properties:

#### *Electric Car Axle, 0.32 Carbon, Acid Steel.*

Tensile strength, lbs. per sq. in. . . . .	91,700
Elastic limit, lbs. per sq. in. . . . .	61,620
Elongation, per cent. in 2 ins. . . . .	33.5
Reduction of area, per cent. . . . .	48.1

In the hardened condition—without subsequent tempering—these steels may be used for gears. In the toughened condition these steels present the maximum resistance to fatigue and other dynamic stresses, as represented by alternating impact and other tests, over any of the straight carbon steels; the dynamic strength probably apexes at about 0.30 per cent. carbon, as far as the author can judge from his own researches and from the work and conclusions of others.

**Untreated.**—In the untreated condition, with standard manganese, phosphorus and sulphur, the average tensile strength of these steels will be about as follows:

Carbon.	Acid Steel.	Basic Steel.
0.25 to 0.30	67,000 to 78,000	63,000 to 72,000
0.30 to 0.35	69,000 to 83,000	65,000 to 74,000

Rolled plates, from 2 to 4 ins. thick, made of basic steel with 0.25 to 0.35 per cent. carbon and about 0.40 per cent. manganese, will usually fulfill the following specifications:

Tensile strength, lbs. per sq. in. . . . .	65,000 to 75,000
Elastic limit, lbs. per sq. in. . . . .	33,000 to 37,000
Elongation, per cent. in 2 ins. . . . .	30 to 25
Reduction of area, per cent. . . . .	50 to 36

These results may also be considered as generally applicable to untreated steel of this analysis, but which has had more or less elaboration or working.

**Heat Treated.**—The upper critical range decreases from about 1500° F. for 0.25 per cent. carbon, to about 1425° F. for the 0.35 per cent. carbon steel. Practical experience has shown that a quenching temperature of 1500° to 1525° F. for the lower carbons of this range, and 1450° to 1500° F. for the higher carbons will give satisfactory results under ordinary conditions. If the heating has been conducted uniformly and not too rapidly—especially when approaching the maximum temperature—the original structure of the steel should be entirely eliminated, as the temperatures recommended are distinctly above the upper critical range. Nevertheless, some metallurgists prefer to quench these steels from a higher temperature, say 1575° to 1600° F., in order to make certain of the complete change in structure and to obtain a maximum hardening effect. In either case, intelligent furnace operation and heat control will probably be the governing factor rather than the indicated furnace temperature or mere theorizing.

For forgings in which especially high qualities are desired, double quenching will produce a refinement of grain and correspondingly higher elastic limit and ductility than are usually obtained by the single treatment. The temperatures recommended for this range of carbons are:

1. First quenching from 1600° F., or from 1500° to 1550° F. if the higher quenching should prove too drastic.



2. Second quenching from 1425° to 1450° F., followed by
3. Suitable toughening according to the size of piece and physical properties desired.

The results to be obtained from heat treatment will vary largely for this range of carbon in particular, due to such influence as the increase of a few points in the carbon content (particularly noticeable in these mild steels), the size of the section, the quenching medium, and so forth. The results given under the 0.15 to 0.25 carbon range, and under the 0.35 to 0.45 carbon range to follow, may be used as a general measure of the carbons under discussion. Stated roughly, these carbons will give elastic limits ranging from 35,000 to 80,000

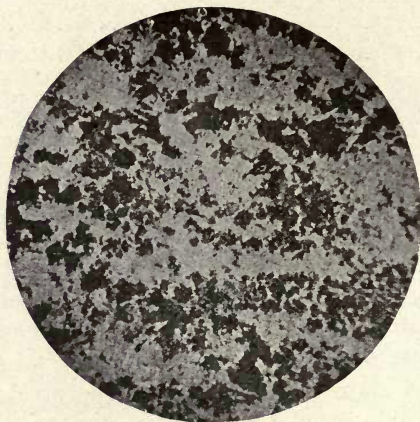


FIG. 146.—0.28 per cent. Carbon Steel.  $\times 39$ . (Campbell.)

lbs. per square inch, with corresponding elongations of 30 to 10 per cent. in 2 ins.

**Annealed.**—As has been previously explained, heating for annealing to just above the  $A_{c1}$  (lower) critical range will refine the ground-mass only, while complete refinement is shown by the disappearance of the ferrite and network beyond the upper critical range ( $A_{c3}$ ). As an example of this, examine the photomicrographs of a basic open-hearth steel containing 0.28 per cent. carbon and 0.52 per cent. manganese, as shown in Figs. 146, 147 and 148. The first photograph shows the original steel with its coarse, weak structure. Fig. 147 shows the same steel annealed at 1425° F., or just over the  $A_{c1}$  range; the pearlitic ground-mass has been entirely refined, but there still remains the unabsorbed and undiffused excess ferrite. Fig.

148 shows the same still heated to 1520° F. and slow cooled in the same manner; but in this case the structure has been entirely changed and refined by heating to a temperature over the upper critical range.



FIG. 147.—0.28 per cent. Carbon Steel Annealed at 1425° F.  
×39. (Campbell.)

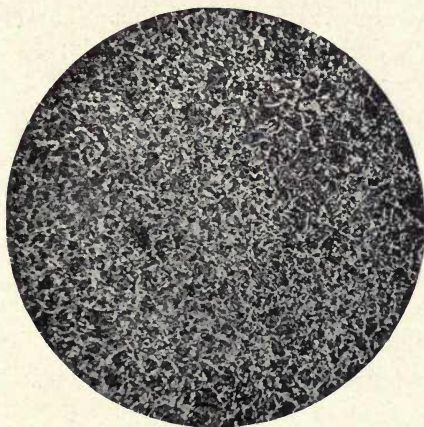


FIG. 148.—0.28 per cent. Carbon Steel Annealed at 1520° F.  
×39. (Campbell.)

Practical experience has shown that a temperature of 1500° to 1525° F. will give excellent results for the full annealing of steels within this range of carbons. On account of the hardening effect of air cooling steels with over 0.20 per cent. carbon when in small

sections, these steels should be slow cooled, either in the furnace, in lime or in ashes.

In regard to the physical properties to be obtained from the annealing of these steels, the lower carbons of this range should always meet the U. S. Government specification of:

Tensile strength, lbs. per sq. in.....	60,000
Elastic limit, lbs. per sq. in.....	30,000
Elongation, per cent. in 2 ins.....	30

while the higher carbons will usually give:

Elastic limit, lbs. per sq. in.....	35,000 to 45,000
Elongation, per cent. in 2 ins.....	22 to 32
Reduction of area, per cent.....	30 to 60

#### 0.35-0.45 CARBON STEEL

Straight carbon steels with 0.35 to 0.45 per cent. carbon are particularly suited to medium and heavy forgings for which the lower carbons would not give sufficient strength, and for which it is also not desirable to use water quenching on account of the possibility of starting incipient cracks or strains. This steel is commonly used for high-duty and moving machine parts; for axles, side bars, crankpins and other locomotive forgings; for guns and gun forgings; for crank shafts, driving shafts and similar automobile parts; and for general structural purposes requiring the combination of maximum strength with minimum brittleness. It has excellent dynamic strength, although probably not quite so much as the previous class of 0.25-0.35 carbon. Steel with 0.40 carbon according to Robin<sup>1</sup> presents the greatest resistance to abrasive action (wear). These steels are easy to machine when in the annealed or soft-toughened condition, but should not be used for screw machine stock.

The upper critical range temperature of this steel is about 1425° F. to 1400° F.

**Untreated.**—The average untreated American open-hearth steel with standard manganese, phosphorus and sulphur will average about as follows in tensile strength:

Carbon.	Acid Steel.	Basic Steel.
0.35 to 0.40	78,000 to 92,000	70,000 to 78,000
0.40 to 0.45	87,000 to 100,000	76,000 to 89,000

<sup>1</sup> J. Robin, Inst. Journ., II, 1910.



**Annealed.**

Remarks.	C.	Mn.	Phos.	Sul.	Tensile Strength. Lbs. per Sq. In.	Elastic Limit. Lbs. per Sq. In.	Elongation. % in 2 Ins.	Red. of Area. Per Cent.
General limits....	0.35 to 0.45	not over 0.70	under 0.045	under 0.045	70,000 to 85,000	38,000 to 50,000	28 to 20	55 to 40
Forged gun jacket acid steel.....	0.35	0.25	0.038	0.019	77,080	39,500	27	
Forged gun jacket basic steel.....	0.43	0.22	tr.	0.023	78,180	43,100	25.5	
8-in. axle acid steel annealed at 1400° F.....	0.42	0.51			78,420	47,460	28	54.5

**Heat-treated.**—Large sections, when quenched in good mineral oil from 1400° to 1500° F., and toughened at 900° to 1200° F. (according to the carbon content and largest section), should always meet the specification of 85,000—50,000—22—45. The following tests taken from large forgings show the variety of combinations of strength and ductility which may be obtained:

Forging.	Carbon.	Treatment.	Tensile Strength. Lbs. per Sq. In.	Elastic Limit. Lbs. per Sq. In.	Elongation. Per Cent. in 2 Ins.	Red. of Area. Per Cent.
Gun jacket	0.35	1500—o/1200	109,560	65,090	16.5	
Axle.....	0.41	1450—w/1000	90,250	54,575	25.4	52.4
Gun jacket	0.43	1500—o/1200	111,100	69,700	17.0	
Shaft.....	0.42	1525—o/1300	82,040	57,060	29.0	55.0

o = oil. w = water.

It is always advisable to keep the drawing temperature as near 1200° to 1250° F. as possible, not only because it is easier for the furnace operator to obtain more accurate temperature control at these more readily distinguished “reds,” but also on account of the greater dynamic strength which is obtained by the use of the higher drawing temperatures.

The results obtained from the water quenching from 1450° F. and subsequent toughening of small rounds of 0.40 per cent. carbon steel are given in the chart in Fig. 149.

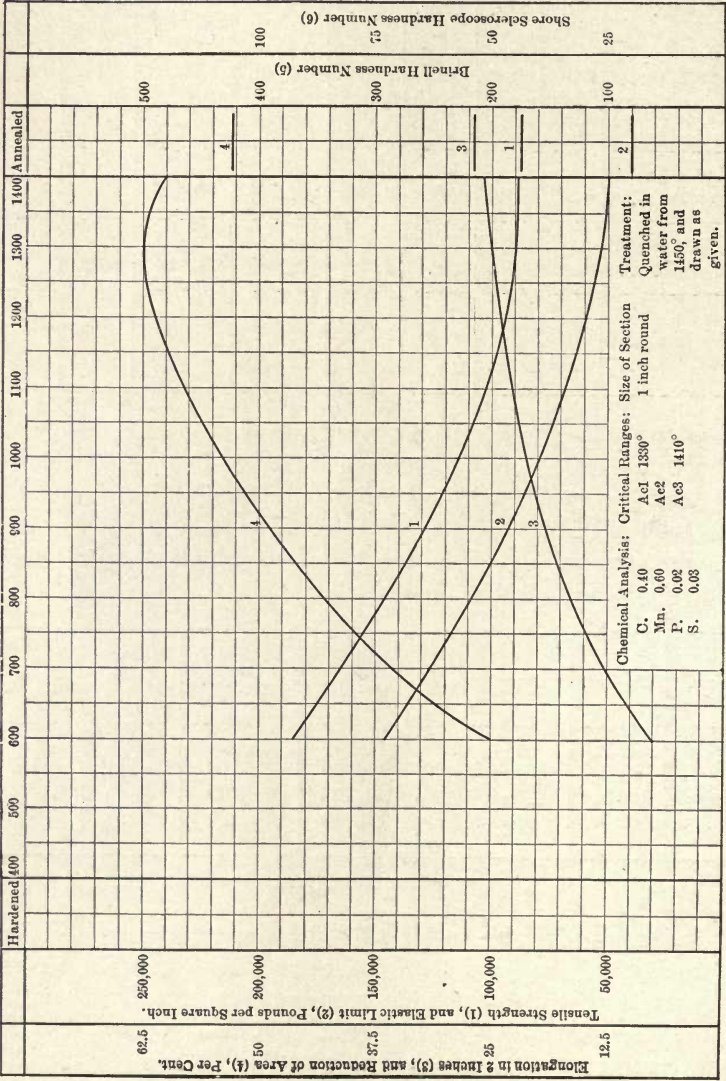


Fig. 149.—Normal Characteristics of 0.40 Carbon Steel, Heat Treated.

## LOCOMOTIVE AXLES

Locomotive axles and other heavy forgings used in locomotive construction are illustrative of the treatment of pieces of large section of the above carbon range.

**Heat-treated Axles.**—For heat-treated axles the carbon content will range between 0.35 and 0.50 per cent., and with such steel the treatment may generally be adjusted to meet the standard specification of:

Tensile strength.....	85,000 lbs. per sq. in.
Elastic limit.....	50,000 lbs. per sq. in.
Elongation.....	22 per cent. in 2 ins.
Reduction of area.....	45 per cent.

The quenching of the axles, usually from temperatures of 1400° to 1500° F., is mainly a proposition of correct heat application and efficient handling. Both oil and water are used extensively for hardening axles. Water will bring out the full effect of heat treatment by giving the highest tensile test properties of which the steel is capable; with the same ductility, oil quenching will give lower tensile values than water quenching. A steel with lower carbon content may more logically be used with water quenching than with oil. Water requires no expensive cooling nor circulation system, and has practically no cost of upkeep or replenishment, as all these may be regulated by the intake of fresh, cold water. On the other hand, many engineers severely condemn the use of water in that it is too harsh in its action upon large masses of steel—as in axles, that cracks are more liable to develop, and that internal strains are set up which often are not always entirely relieved by the reheating or toughening. Oil is much the safer quenching medium to use for axles, will give more uniform results, and should only be replaced by water for economic reasons.

The hardened axles are charged while still warm into the reheating furnace, which is maintained at such temperature as will relieve all strains set up in the hardening and at the same time give the physical properties desired. This temperature will vary between 900° and 1200° F., depending upon the chemical composition of the steel. The higher the drawing temperature, the more ductile the steel and apparent coarseness of the grain, due to the transformation of the transition constituents troostite and sorbite into pearlite plus free ferrite. Straight carbon steels quenched in water and drawn at 1000° or 1100° F. will be entirely sorbitic, but



at 1200° may show considerable free ferrite. Too much emphasis cannot be given to the necessity of keeping a uniform temperature and allowing sufficient time for the heat thoroughly to penetrate the axle. It is then preferable for the axles to cool with the furnace, rather than to remove them while still at the toughening temperature.

The temperatures used by one manufacturer of acid steel axles and other large forgings to meet the standard A. S. T. M. specifications are as follows: after quenching in oil from 1450° F., reheat as below and air-cool or cool in ashes.

0.42 to 0.45 per cent. carbon.....	1175° F.
0.38 to 0.42 " " " .....	1125° F.
0.33 to 0.38 " " " .....	1075° F.
0.28 to 0.33 " " " .....	1000° F.

The following are characteristic tests from Open-hearth steel locomotive axles (Penna. R.R.):

#### 0.41 Carbon

	Forged.	Treated, 1500° water/1000° F.
Tensile strength.....	73,627	90,250
Elastic limit.....	31,505	54,575
Elongation.....	31.6	25.4
Reduction of area.....	43.6	52.4

#### 0.50 Carbon

	Forged.	Treated, 1500° water/1200° F.
Tensile strength.....	83,430	90,092
Elastic limit.....	34,370	53,655
Elongation.....	22.6	27.1
Reduction of area.....	30.0	52.8

**“Tempered” Axles.**—For want of a better name, under this heading might be included such as are treated by the “Coffin” or similar processes. The main principle consists in heating the axle as usual for hardening, then immersing in the quenching bath for a calculated number of seconds, immediately withdrawing, and allowing the heat from the interior of the axle to “temper” the part which had been hardened by the short immersion in the oil or water. This process has been developed to such a nicety that surprisingly uniform results may be obtained if the test is always taken from the same relative place, such as half-way between the center and the outside. The main arguments for the process are that it is simple

and that the axle will have a tough (annealed) core, and, at the same time, a hard wearing surface. Non-uniformity of structure is the principal argument of those condemning the process, and on account of the inevitable "human equation" which enters into it, would seem to be not without justice in many instances.

**Annealed Axles.**—The axles are heated up slowly and uniformly to a temperature slightly in excess of the upper critical range, maintained at this temperature for sufficient time for the steel to respond to the heat, and then cooled with the furnace. If the working and the finishing temperature during forging have been adjusted so as to give a fine grain to the steel, besides good physical test results, it will be found that heating to a temperature over the critical range may not be necessary in many instances. Where it is necessary to anneal large numbers of heavy axles, the hot axles may be removed quickly to a pit and covered with lime or ashes. Annealing alone will generally overcome the strains set up in the previous processes of manufacture, but it does not bring out the higher physical properties of which the steel is capable. Annealed axles will show pearlite and free ferrite, the apparent size of the ferrite grains depending upon the rate of cooling and the time thus given for the ferrite to separate out from the matrix.

In order to obtain the required tensile strength upon annealing it is necessary to use a steel of higher carbon content than that used for full heat treatment. A tensile strength of 80,000 lbs. per square inch will require a 0.50 carbon steel or higher. A temperature of 1500° F. is generally recommended (A. S. T. M.) for annealing 0.40 to 0.60 per cent. carbon steel, but since the critical range of this steel is about 1400° F. or a little under, an annealing temperature of 1400° to 1450° F. will give a better fracture, together with a better combination of tensile strength and ductility.

The author has had much better results with the lower temperature, although the time required for the annealing generally is longer. The following results from acid open-hearth steel will show the effect of the lower temperature anneal:

Heat 4261	Annealed at 1406°	
Carbon, 0.42 per cent. . . . .	Tensile strength . . . . .	78,420 lbs. per sq. in.
Manganese, 0.51 per cent. . .	Elastic limit. . . . .	47,460 lbs. per sq. in.
Phosphorus, 0.034 per cent. . .	Elongation in 2 ins. . . .	28 per cent.
Sulphur 0.028 per cent. . . .	Reduction of area. . . .	54.6 per cent.

**Failures of Heat-treated Axles.**—Aside from piping, segregation, and other impurities in the steel, improper heat treatment is the active cause of failure of both heat-treated carbon and alloy steel axles. Unequal or insufficient heating in either the hardening or toughening processes will produce unequal stresses, which in turn will sooner or later result in failures. These failures are always transverse, and never longitudinal. Water quenching large sections has a strong tendency to produce cracks, often not appearing on the surface, and which may open up when subjected to the heavy duty and “pounding” when placed in service. Such defects may be sometimes discovered by the drop test, but its expense prevents many railroads from using it for the test of every axle. Heat-treated axles, when given ample reduction in the forging operation, carefully and uniformly heated to the proper temperatures, and held at those temperatures for a time sufficient for the steel to respond throughout, should prove vastly superior to untreated or annealed axles.

On the other hand, the engineering departments of many railroads have become considerably alarmed over the frequent failures of so-called “heat-treated” axles, and many have absolutely refused to have anything to do with axles which have been oil or water quenched. This really serious phase of the axle question has led to the investigation of the possibilities of hardening such forgings in *air* or *steam*. Surprisingly good results have been obtained by methods based upon this system—and from the technical standpoint are indeed remarkable, since a considerable toughening heat is necessary with even 0.40 per cent. carbon steel.

#### 0.45–0.60 CARBON STEEL

**Treatment of Large Sections.**—As the carbon content is progressively increased beyond 0.45 per cent., its effect becomes quite noticeable in the added brittleness of the steel. This is strongly illustrated by the fact that a general study of heat-treatment practice will show that there is very little quenching of large sections when the carbon content exceeds the 0.50 per cent. mark. The dangers to be encountered, both in the treatment itself and by possible fracture in service, almost prohibit such treatment of large sections. Any increase in static strength which can be obtained by quenching and toughening is most certainly acquired with the ever-present danger of cracking, or of starting incipient cracks. For these reasons it is, therefore, apparent that the full heat treat-



ment of large sections, even though it may bring out higher physical characteristics in the steel—as is shown by the subsequent figures obtained from the treatment of a 0.50 per cent. carbon axle—is becoming less and less of a factor in steels of these carbons.

*0.50 Per Cent. Carbon Axle*

	Forged.	Quenched in Water from 1400° F. Toughened at 1200° F.
Tensile strength, lbs. per sq. in. ....	83,430	90,090
Elastic limit, sq. in. ....	34,370	53,655
Elongation, per cent. in 2 ins. ....	22.6	27.1
Reduction of area, per cent. ....	30.0	52.8

**Tempering, and Small Sections.**—On the other hand, the hardening and *tempering* (as distinguished from *toughening*) of the smaller sections, such as gears, dies, etc., begins to take an important place in heat-treatment work with these carbons. In such cases the increased-carbon content brings about an inherently possible wearing hardness which is developed by hardening and tempering. The medium and smaller size sections may be satisfactorily hardened in water with but a small proportion of the danger which would inevitably result from the water quenching (or even oil quenching) of larger sections. And, by varying the reheating temperatures, the following approximate physical results may be obtained:

Elastic limit, lbs. per sq. in. ....	50,000 to 110,000
Elongation, per cent. in 2 ins. ....	20 to 5
Reduction of area, per cent. ....	50 to 15

**Annealing.**—The commercial annealing of steel of say 0.50 to 0.60 per cent. carbon will give a variety of results which in themselves have proven a stumbling block for many a heat treater. This is largely due to the prominent part and effect of different rates of cooling in relation to the size or mass of the steel. To illustrate: 6×6 in. billets of 0.50 to 0.55 carbon which have been heated to 1400° F. and furnace cooled will, in general, meet the specifications of

Tensile strength. ....	80,000
Elastic limit. ....	40,000
Elongation. ....	22
Reduction of area. ....	35

On the other hand, smaller sections, annealed in the same manner and in the same furnace, will according to their size, give physical results varying anywhere between

Elastic limit.....	45,000 to 60,000
Elongation.....	20 to 15
Reduction of area.....	40 to 30

In other words, the extreme variability in the rate of cooling, as dependent upon the size of section and mass of the steel, its relation to the size of the furnace, the degree to which the cooling of the furnace may be controlled, and numerous other related factors make the commercial annealing of these steels an individual problem as far as actual physical results are concerned.

It is therefore always advisable, if specific physical results must be obtained by annealing (used in the broad interpretation of the term), to take first a preliminary test of the steel in the condition as received. From such results it will then be evident how much the steel must be "let down," and the proper reheating temperature may be judged from previous experience or by experiment. Although annealing at a temperature under the critical range will not change the general structure of a pearlitic steel, it will relieve the strains and stresses, and thereby improve the steel. But further, the previous elaboration, such as rolling or forging, which the steel has undergone, will, in a majority of cases in actual practice, leave the steel in more or less of a sorbitic state. Under such conditions, a reheating—or commercial annealing—will actually change the physical results, even though the annealing temperature is *under* the critical range.

Such commercial annealing or reheating temperatures may vary from 900° F. and upwards through the upper critical range. In the author's experience there is little or no change in the physical test results through the annealing of such steel at temperatures under 900° F. or thereabouts. But from this temperature upwards the sorbitic constituents will gradually coagulate into the pearlite and ferrite, with a corresponding lowering of the static strength and increase in the ductility. Consequently, by regulating the commercial annealing temperature, the physical results may be "let down" to the desired limits.

If it is desired to change entirely the structure of the steel and to obtain the finest grain size possible, with maximum ductility, it

will be necessary to anneal the steel at a temperature slightly in excess of the upper critical range, followed by slow cooling.

The influence of the rate of cooling, as exerted by air cooling, is manifested in the peculiar statement that the tensile strength of these hard forging steels may be actually raised by annealing (as distinguished from quenching). It is a well-known fact that steel of such carbon content when cooled in air at a more or less rapid rate through the critical range will take on a noticeable degree of hardness. The author has found that this fundamental principle may be applied to great advantage in the treatment of axles—with, of course, certain modifications—and that it is even necessary to reheat or toughen in order to lower the tensile strength and obtain the proper ratio of static strength to ductility. Such a process is now being developed by a large manufacturer of axles, and will in all probability have an influence upon the heat treatment of axles and other forgings of large section.

#### SHRAPNEL

Shrapnel are illustrative of this range of carbon and of pieces of medium section.

The current specifications for foreign shrapnel cover a wide range of physical properties, varying between 80,000 and 140,000 lbs. per square inch in tensile strength, with 20 to 8 per cent. elongation. The chemical composition of the steel used will be approximately between 0.50 and 0.60 per cent. carbon, although the extreme limits are 0.35 to 0.8 per cent., 0.4 to 1.0 per cent. manganese, phosphorus, sulphur and silicon about normal, and with or without the addition of chrome or nickel. Thus, according to the physical or chemical specifications worked under, some shrapnel manufacturers have been able to meet their particular specifications without any treatment except perhaps cooling the cases in lime after forming; others have had to anneal, or harden and temper; while still others have had to carry out all three heating operations.

There is nothing unusual in the heat treatment required. The proposition in short is merely one of *proper heat application* in furnaces of correct design and construction; and yet one may see almost any and every kind of a furnace being operated in almost any and every kind of a way except the right one, with the result of large rejections.

The latest and a very efficient type of furnace for this work is



designed on underfired principles, with a continuous and automatic charging and discharging of the shrapnel. The cycle for the complete hardening and drawing is as follows: one man places the rough-formed shells on the charging platform of the hardening furnace, as shown in Fig. 149a; an automatic device takes the shrapnel into and through the heating chamber at a specified and predetermined rate; the heated shrapnel are then discharged continuously from the furnace into an oil-quenching bath, as shown in

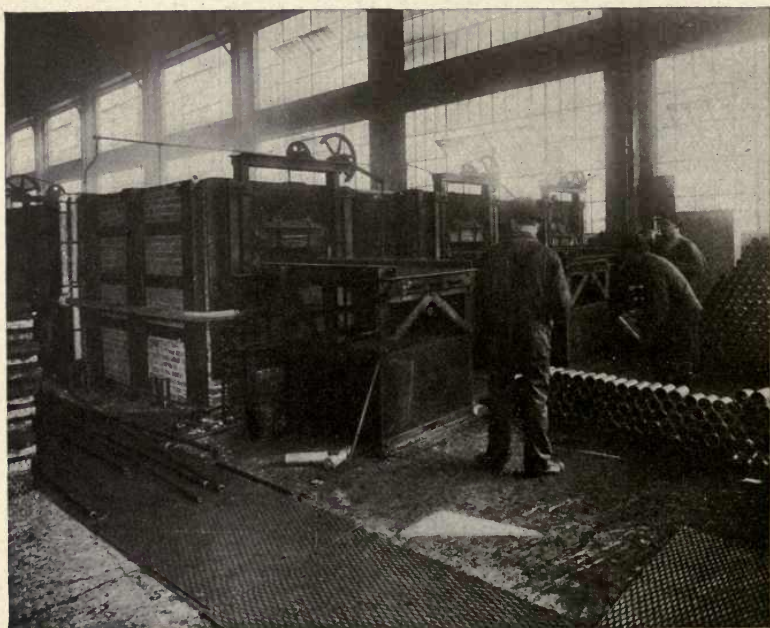


FIG. 149a.—Automatic Hardening Furnaces, Charging End, Working on 3-in. Shrapnel.

Fig. 149b, from which they are removed by a conveyor system and delivered to a table in front of the second or drawing furnace. Here another man takes them from the table and places them on the charging table, as shown in Fig. 149c; the shrapnel then follow the same course as in the first furnace, except that they are received from the furnace into wheelbarrows or similar means of taking them away, as shown in Fig. 149d. The actual temperature of the shrapnel in the case of one plant was 1500° F. for hardening and 850° F. for the tempering or drawing operation.

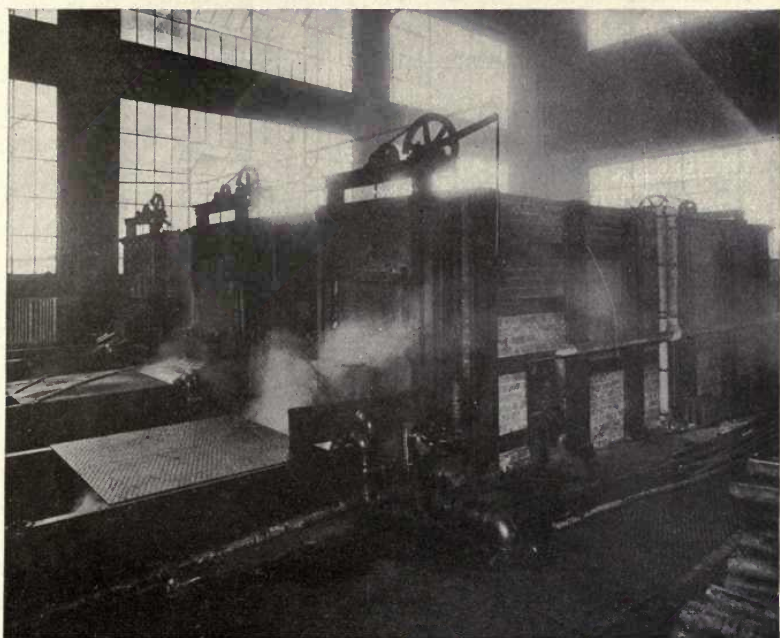


FIG. 149b.—Hardening Furnaces, Discharge End; Oil Quenching Tanks at the Left.

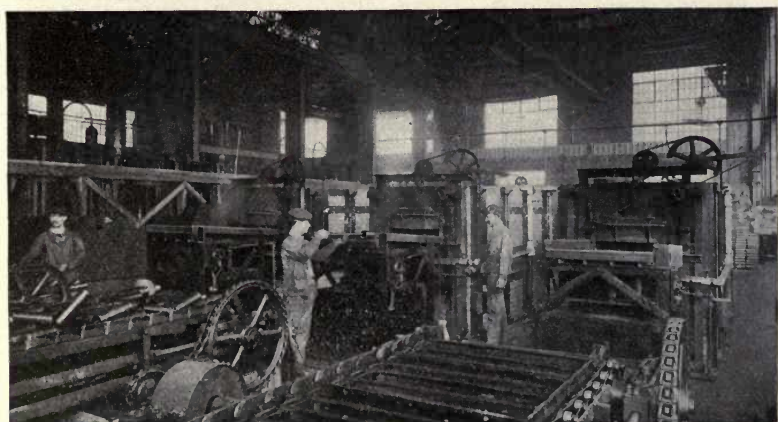


FIG. 149c.—Tempering Furnaces—Charging End—Conveyer from Quenching Tank.

In connection with the above equipment a comparison between the old hand method and the new automatic appliances is extremely interesting. The following are actual tests made in the same plant on 3.3-in. shrapnel:

*Old Practice*

Two furnaces, 6 men to each furnace:

One furnace, 6 men, 910 shells in 10 hours

One furnace, 6 men, 1207 " " " "

Total, two furnaces, 12 men, 2117 " " " "

Average of 176 shells per man per 10 hours.

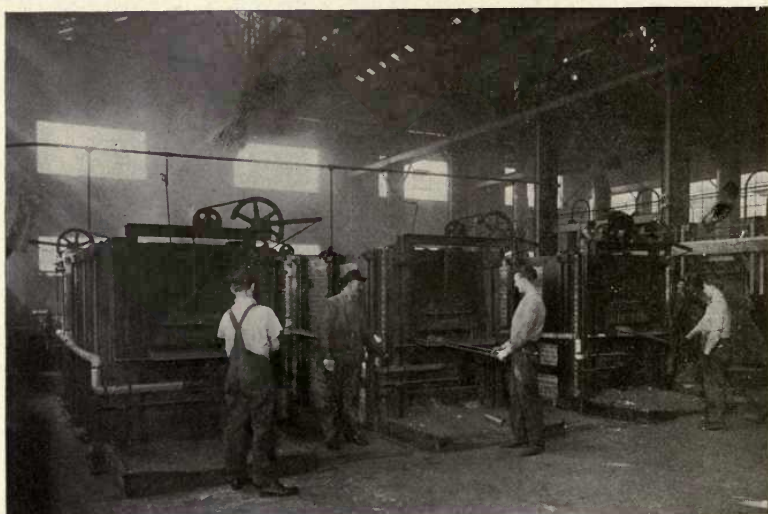


FIG. 149d.—Tempering Furnaces—Discharge End.

*New Practice*

Two furnaces, with 3 men total:

One furnace, 2508 shells in 10 hours

One furnace, 2603 " " " "

Total, two furnaces, 3 men, 5111 " " " "

Average of 1704 shells per man per 10 hours.

In addition to obtaining some 1000 per cent. increased output per man with the new underfired, automatic furnace, it has been shown that in the old method the average rejections were running around 15 to 20 per cent., and were only about 3 per cent. for the new practice.



## CARBON STEELS WITH OVER 0.60 CARBON

**Treatment in General.**—The treatment of high-carbon steel develops into the two propositions of hardening and annealing. Toughening, as referring to high reheating temperatures subsequent to hardening, is but very little used, due to the fact that these steels are too brittle for ordinary structural purposes. Similarly, tempering is governed entirely by the degree of hardness required by the tool and is dependent, not only upon the chemical analysis, but in a larger measure upon the result of the hardening operation.

**Hardening.**—The precautions to be adopted in hardening may be repeated in the following general summary:

- (1) Use the lowest temperature which will give the desired results.
- (2) Heat slowly and uniformly.
- (3) The higher the carbon content, the greater is the degree of care which must be used, and, in general, the more narrow the hardening temperature limits.

The temperatures to be used in hardening are largely governed by the carbon content, and which, in turn, influences the position of the critical range. We may sum up these factors as follows:

Carbon Content. Per Cent.	Critical Range. °F.	Hardening Temperature. °F.
0.60	1340-1380	1400-1460
0.70	1340-1375	1400-1450
0.80	1340-1365	1390-1450
0.90	1340-1360	1375-1450
1.00	1340-1360	1375-1450
1.10	1340-1360	1375-1430
1.20	1340-1360	1375-1430
1.30	1340-1360	1375-1420
1.40	1340-1360	1375-1420

In giving the above hardening temperatures we have assumed that the previous mechanical and heating operations have left the free cementite (in hyper-eutectoid steels—greater than 0.9 per cent. carbon) well distributed, or emulsified, throughout the steel. This will generally be true when the proper finishing temperatures, either in rolling or in forging, have been used. In such cases, therefore, it will not be necessary to heat to above the Ac<sub>cm</sub> range in order to emulsify the free cementite, and following with a subsequent quenching from slightly above the principal critical range.

If, however, the previous heating operations have left the free cementite in the form of spines or network, it will be mandatory to use the double-quenching method in order to spheroidalize this free cementite and thus obtain the maximum wearing and cutting hardness; for details of such procedure the subject matter in Chapter VII should be studied.

**Annealing.**—The general subject of annealing hyper-eutectoid steels has been discussed in Chapter III. A series of physical test results of experiments carried out by Fábry<sup>1</sup> upon the annealing of steels with carbon contents of 0.58 to 1.36 per cent., the size of bar being 1.18 ins. square, and the selected annealing temperatures being maintained for three hours, are given in the following tables:

0.58 PER CENT. CARBON STEEL—ANNEALED

Treat- ment.	Tests.				Hard- ness.	Microscope.	
	Tensile Strength, Lbs. per sq. in.	Elastic Limit, Lbs. per sq. in.	Elonga- tion, per cent in 3.15 ins.	Red. of Area, per cent		Structure.	Notes.
Annealed Deg. Fahr.					Brinell No.		
1110	99,540	—	15.8	43.4	196	Free ferrite and pearlite.	Ferrite reticulated, meshes filled with grainy pearlite.
1200	98,420	45,510	17.7	49.0	183		Ferrite begins to change into pearlite.
1290	84,200	39,820	20.7	59.2	174	Smaller ferrite crystals and pearlite.	Structure essentially differing from other specimens, because the ferrite is uniformly distributed.
1380	93,860	36,980	18.6	43.4	176		
1470	96,860	39,820	19.1	36.8	187	Free ferrite and pearlite.	Ferrite forms a network; pearlite partly grainy, partly lamellar.
1560	96,710	39,820	17.9	35.6	183		
1650	98,130	39,820	18.6	36.8	185		
1740	93,860	36,980	16.7	33.6	187		Network of large ferrite crystals filled with pre- dominantly grainy pearlite.
1830	100,700	39,820	13.1	25.2	196		

Critical range Ac commences at 1337°, maximum at 1355°.

<sup>1</sup> Zs. Fábry, "The Variation in the Mechanical Properties and Structures of a Few Special Tool Steels Annealed between 600° and 1000° C." Int. Soc. Tes. Mat., 1912.

## 0.81 PER CENT. CARBON STEEL—ANNEALED

Treat- ment.	Tests.				Hard- ness.	Microscopic.
Annealed Deg. Fahr.	Tensile Strength, Lbs. per sq. in.	Elastic Limit, Lbs. per sq. in.	Elonga- tion, per cent in 3.15 ins.	Red. of Area, per cent	Brinell No.	
1110	102,950	—	13.1	37.6	212	
1200	106,400	42,670	14.0	35.6	207	
1290	99,540	39,820	17.8	43.4	187	
1380	100,700	31,290	14.6	29.4	183	
1470	102,840	31,290	12.5	14.8	196	
1560	105,250	36,980	13.1	23.0	187	
1650	100,400	31,290	13.1	19.4	203	
1740	98,980	31,290	10.2	14.0	207	

Critical range Ac commences at 1328°, maximum at 1337°.

## 0.92 PER CENT. CARBON STEEL—ANNEALED

Treat- ment.	Tests.				Hard- ness.	Microscopic.	
Annealed Deg. Fahr.	Tensile Strength, Lbs. per sq. in.	Elastic Limit, Lbs. per sq. in.	Elonga- tion, per cent in 3.15 ins.	Red. of Area, per cent	Brinell No.	Structure.	Notes.
1110	122,900	—	12.0	23.0	228	Eutectic.	Grainy pearlite with larger grains.
1200	120,600	42,670	13.0	25.2	217		
1290	98,420	36,980	11.5	33.6	163		Structure perfectly homo- geneous and essentially differing from those of other specimens.
1380	91,030	34,130	17.8	43.4	174		
1470	113,500	31,290	10.5	14.8	212		Grainy pearlite.
1560	112,100	—	9.1	14.0	207		
1650	112,500	31,290	8.7	14.8	216		Lamellar pearlite.
1740	105,800	31,290	9.0	11.6	214		
1830	123,450	36,980	6.8	9.2	228		Indications of overheated structure.

Critical range Ac begins at 1346°, maximum at 1355°.



## 1.11 PER CENT. CARBON STEEL—ANNEALED

Treat- ment.	Tests.				Hard- ness.	Microscopic.	
Annealed Deg. Fahr.	Tensile Strength, Lbs. per sq. in.	Elastic Limit, Lbs. per sq. in.	Elonga- tion, per cent in 3.15 ins.	Red. of Area, per cent	Brinell No.		
1110	12°,550	—	9.7	20.8	248		
1200	126,300	51,200	12.6	23.0	235		
1290	108,650	54,040	10.3	23.0	185		
1380	88,180	39,820	19.6	49.0	170		
1470	91,590	36,980	16.7	36.8	178		
1560	96,700	25,600	10.3	18.6	196		
1650	105,100	29,580	6.1	10.0	207		
1740	100,700	25,600	6.6	9.2	202		
1830	116,050	36,980	6.0	6.8	228		

Critical range Ac begins at 1337°, maximum at 1346°.

## 1.36 PER CENT. CARBON STEEL—ANNEALED

Treat- ment.	Tests.				Hard- ness.	Microscopic.	
Annealed Deg. Fahr.	Tensile Strength, Lbs. per sq. in.	Elastic Limit, Lbs. per sq. in.	Elonga- tion, per cent in 3.15 ins.	Red. of Area, per cent	Brinell No.	Structure.	Notes.
1110	132,550	—	6.2	11.6	262	Free cementite and pearlite.	Cementite reticulated, meshes filled partly with lamellar, partly with grainy pearlite.
1200	129,700	67,980	8.5	14.0	255		Free cementite begins to change into pearlite.
1290	123,450	48,355	9.6	16.2	288	Fine-grained cementite.	Structure appears uniform.
1380	93,300	45,510	14.6	37.6	192		As before, grains finer.
1470	90,310	47,500	17.3	36.8	187	Free cementite and grainy pearlite.	Cementite concentrated again into small crystals.
1560	93,300	42,670	13.7	27.4	187		
1650	102,100	32,710	4.5	5.0	209	Free cementite, grainy and lamellar pearlite.	Cementite crystals larger, pearlite partly in lamellæ.
1740	95,580	28,446	4.6	6.8	196	Free cementite and a lamellar pearlite.	Structure essentially altered. Cementite forms a network with large meshes. Steel is over-heated.
1830	101,830	—	2.6	4.4	223		

Critical range Ac begins at 1345°, maximum at 1355°.

## CHAPTER XI

### NICKEL STEELS

**Nickel Steel.**—Nickel may well be said to have been the pioneer among the common alloys now used in steel manufacture. Originally added merely to give increased strength and toughness over that obtained in the ordinary rolled structural steel, the development and possibilities of heat treatment have greatly enhanced its value, so that nickel steel holds a premier position in alloy steel metallurgy.

The chief difficulties attendant upon its use have been its tendency to develop a laminated structure and its liability to seams. But when care is used in its manufacture and rolling, and it is not made in too large heats or ingots, and when piping and segregation are avoided by confining the finished product to that produced from the bottom two-thirds of the ingot, an admirable product for many purposes is obtained.

Nickel steel has remarkably good mechanical qualities when subjected to suitable heat treatment and is an excellent steel for case hardening. In machining qualities it usually takes first place among the alloy steels.

**Strength and Ductility.**—Nickel primarily influences the strength and ductility of steel in that the nickel is dissolved directly in the iron or ferrite, in contradistinction to such elements as chrome and manganese which unite with, and emphasize the characteristics of the cementitic component. Thus, for the forging grades of ordinary nickel steel in the natural condition, the addition of each 1 per cent. of nickel up to about 5 per cent. will cause an approximate increase of 4000 to 6000 lbs. per square inch in the tensile strength and elastic limit over that of the corresponding straight carbon steel, without any decrease in the ductility. This influence of nickel upon the static strength of steel also increases to some degree with the percentage of carbon. To illustrate the effect of nickel upon steel in the natural condition: a steel with 0.25 per cent. of carbon and 3.5 per cent. nickel will have a tensile strength equivalent to that of a straight carbon steel with 0.45 per cent. carbon, a propor-

tionately greater elastic limit, and the advantageous ductility of the lower carbon grade.

**Necessity for Heat Treatment.**—On the other hand, and in connection with the use of alloy steels in general, it should be borne in mind that such steels should be used in the heat-treated condition only—that is, not in either an annealed or natural condition. In the latter conditions there is a benefit, as compared with straight carbon steels and as illustrated above, but often is not commensurate with the increased cost. In the heat-treated condition, however, there is a very marked improvement in physical characteristics. And closely associated with this is the finely divided state of both ferrite and pearlite which characterizes heat-treated nickel steel.

**Nickel vs. the Critical Ranges.**—One of the most interesting phenomena connected with nickel steel is the effect of nickel upon the position of the critical ranges. Nickel, like carbon, has the property of lowering the points of the allotropic transformations of iron, but in a more marked degree. Just as we have seen, in the chapter on Hardening, how “rapid cooling” and “carbon” are “obstructing agents” in preventing the transformation of the austenite into martensite into pearlite, so likewise does nickel act as an obstructing agent. The effect of nickel is obtained through a lowering of the  $A_r$  ranges, so that the temperatures of the critical ranges on cooling may even be brought below atmospheric temperatures. Thus we may have a steel which, without quenching, may be pearlitic, troostitic, martensitic or austenitic, dependent upon the relative percentages of nickel and carbon. Hence, such steels containing nickel may be classified according to their microscopic constituents which are obtained upon slow cooling from a high temperature.

**Classification of Nickel Steels.**—In Fig. 150 there is shown graphically the influence of the nickel-carbon ratio upon the structure of nickel steels as cast, or as moderately cooled from a high temperature.

The “Pearlitic” nickel steels are those in which the critical ranges are all above the ordinary temperatures, so that such steels as slow cooled from a high temperature will consist of pearlite plus ferrite (or cementite). These are the ordinary commercial nickel steels, and are represented by the lower triangle of Fig. 150.

“Martensitic” nickel steels contain that percentage of nickel and carbon which will so lower the position of the critical ranges on cooling that only the partial transformation may proceed. That



is, the austenite is transformed into martensite, but no further—the steel being too rigid to allow a more complete transformation at the low temperatures involved. These steels correspond to the middle triangle in Fig. 150. Nickel steels martensitic throughout have no practical value, as it is impossible to work or machine them. On the other hand, great importance is attached to the use of certain pearlitic nickel steels which can become martensitic upon case carburizing—due to the increased carbon content.

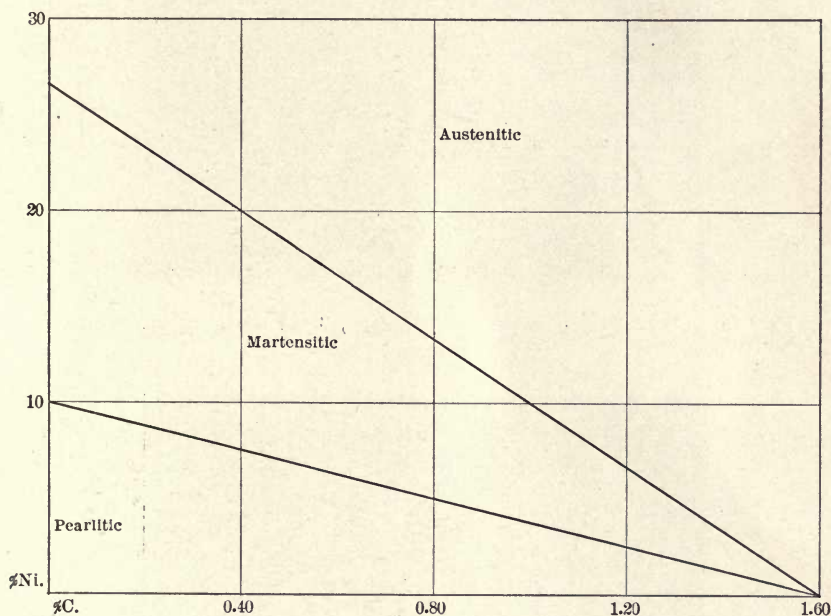


FIG. 150.—Influence of the Nickel-carbon Content upon the Structure of Nickel Steels as Cast.

A still further increase in the nickel or carbon content will cause the critical range on cooling to fall below atmospheric temperatures, so that such steels will be characterized by an “austenitic” or “polyhedral” structure, and are known under these names.

**Micrographic Structure.**—These changes in structure are illustrated by the series of photomicrographs (by Savoia) given in Figs. 151 to 158, all the steels being in the natural condition, having approximately the same carbon content (0.25 per cent.), but with increasing percentages of nickel.

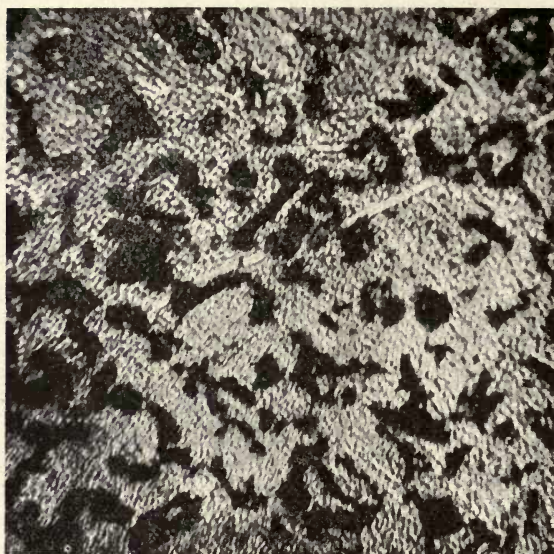


FIG. 151.—Steel with 0.25 per cent. Carbon, 2 per cent. Nickel.  $\times 650$ .  
(Savoia.)

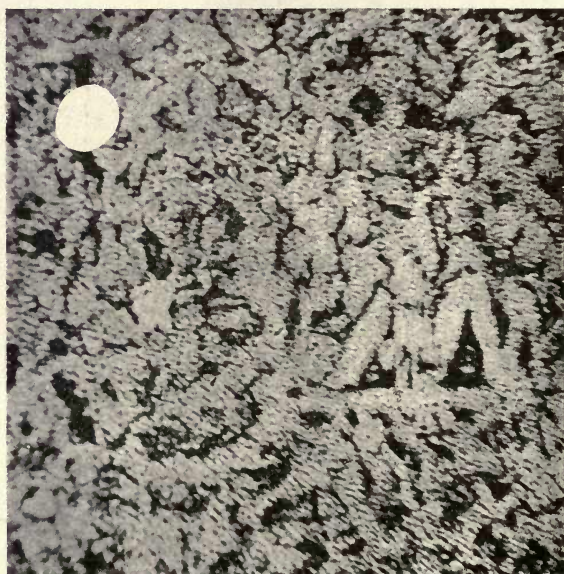


FIG. 152.—Carbon, 0.25 per cent. Nickel, 5 per cent.  $\times 650$ .  
(Savoia.)





FIG. 153.—Carbon, 0.25 per cent. Nickel, 7 per cent.  $\times 650$ .  
(Savoia.)

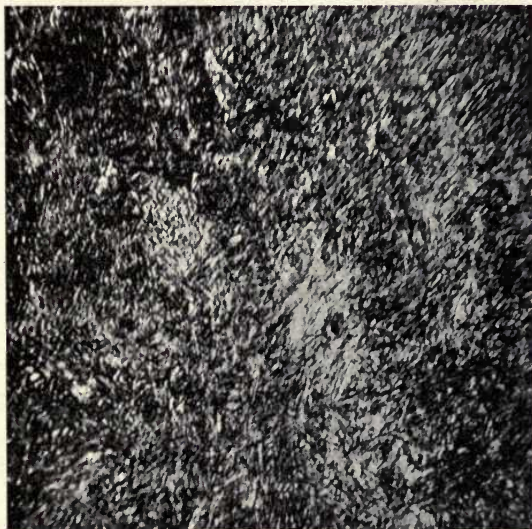


FIG. 154.—Carbon, 0.25 per cent. Nickel, 10 per cent.  $\times 650$ .  
(Savoia.)





FIG. 155.—Carbon, 0.25 per cent. Nickel, 12 per cent.  $\times 650$ .  
(Savoia.)

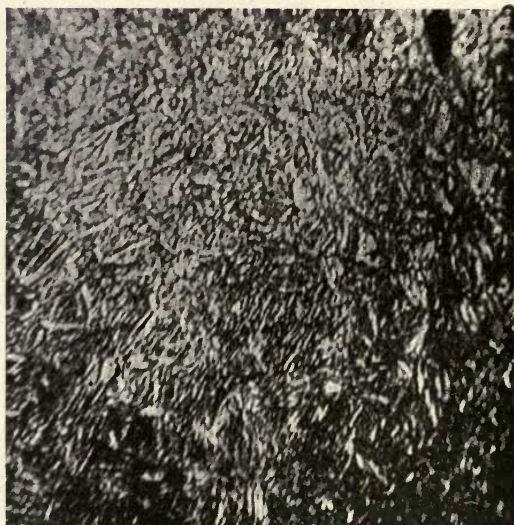


FIG. 156.—Carbon, 0.25 per cent. Nickel, 15 per cent.  $\times 650$ .  
(Savoia.)



FIG. 157.—Carbon, 0.25 per cent. Nickel, 20 per cent.  $\times 650$ .  
(Savoia.)

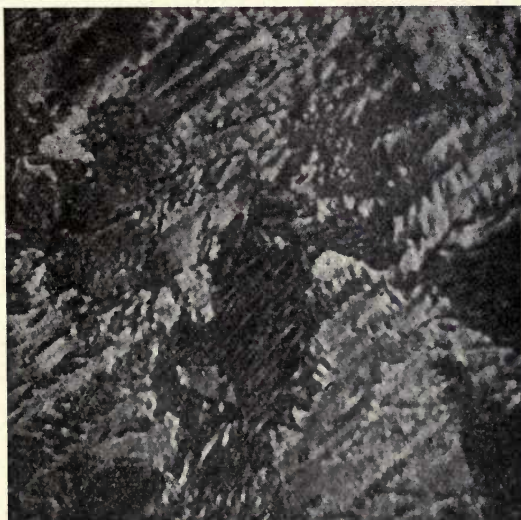


FIG. 158.—Carbon, 0.25 per cent. Nickel, 25 per cent.  $\times 650$ .  
(Savoia.)

It will be seen that the structure of the 2 per cent. nickel steel (Fig. 151) is similar to that of a corresponding straight carbon steel, but is finer and more homogeneous.

The 5 per cent. nickel steel (Fig. 152) shows a still finer and denser structure, in that the pearlite is more divided and distributed.

With the 7 per cent. nickel (Fig. 153) the ferrite and pearlite are still seen, but they are distributed in a special manner as if disturbed by the approach of a transformation. A tendency to orientate, somewhat like martensite, is also noticeable.

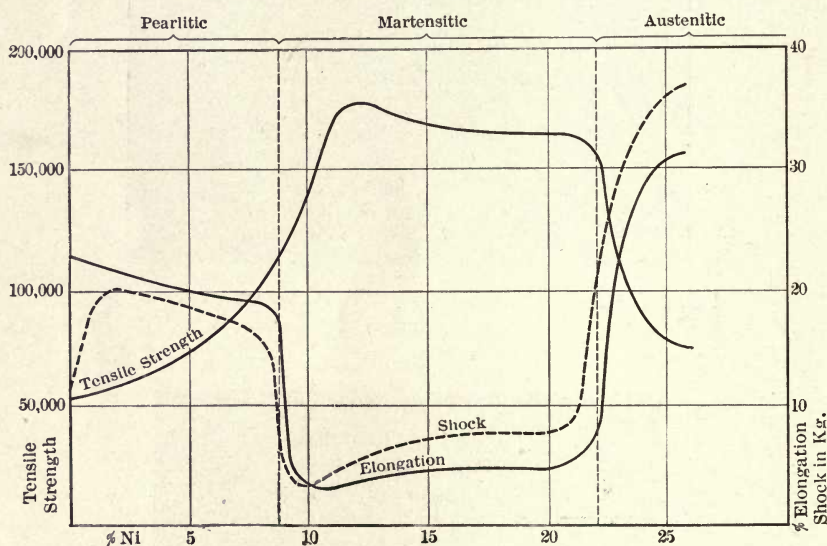


FIG. 159.—Comparative Physical Properties of Nickel Steels with 0.25 per cent. Carbon.

The steels with 10 and 12 per cent. nickel (Figs. 154 and 155) are both wholly martensitic.

With the 15 per cent. nickel (Fig. 156) intensely white constituents appear amidst the martensite and probably represent the first appearance of austenite. The latter increases quite noticeably in the steel with 20 per cent. nickel (Fig. 157), taking on its polyhedral form.

At 25 per cent. nickel (Fig. 158) the whole steel is characterized by large polyhedra of gamma-iron.

**Physical Properties with Increasing Nickel.**—The physical properties of these same cast nickel steels are plotted graphically in



the chart in Fig. 159. It will be noted that the abrupt changes in the curves correspond very closely with the theoretic structure given by the upper abscissæ; and that these same physical properties are indicative of the essential characteristics of pearlite, martensite and

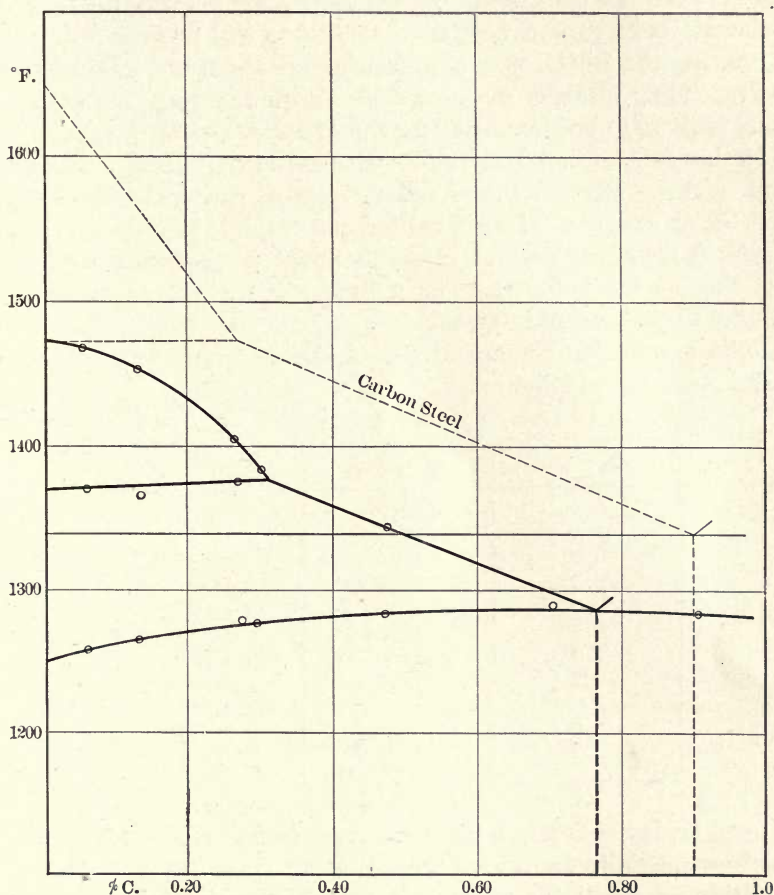


FIG. 160.—Critical Changes on Heating 3 per cent. Nickel Steel.

austenite, as denoted by the tensile strength, ductility (elongation) and resistance to shock.

**Critical Range of Pearlitic Steels.**—For nickel steels with less than 5 to 7 per cent. nickel, each 1 per cent. nickel lowers the critical range (Ac1) on heating by about 15° to 20° F., and also lowers the Ar1 range (cooling) by about 30° to 40° F., below those of the

corresponding ranges for straight carbon steels of the same carbon and manganese contents. Similarly, there is a corresponding lowering of the other critical ranges.

This is graphically shown in Fig. 160, which the author has carefully plotted from a series of observations obtained with 3 per cent. nickel steels of various carbon contents. It will be seen from this curve that the critical ranges on heating are about 60° F. below the corresponding straight carbon steels. With the very low carbons there appears to be a tendency for the Ac3 curve to flatten out; this is further substantiated by results with steels containing 5 to 7 per cent. nickel. Beyond the eutectoid ratio of carbon it was found that the Ar range would begin to drop quite rapidly (not shown in the diagram) below its normal value, as might be expected from the fact that an increase in carbon in these steels act in an analogous manner to an increase in nickel.

The approximate temperatures of the Ac1 and Ar ranges for nickel steels are as follows;

Per Cent. Nickel.	Ac1, ° F.	Ar, ° F.
0	1340	1280
1.0	1320	1240
2.0	1300	1200
2.5	1290	1180
3.0	1280	1160
3.5	1270	1140
4.0	1260	1120
4.5	1250	1100
5.0	1240	1080
6.0	1220	1040
7.0	1200	1000

It must be borne in mind, however, that the Ac1 temperatures may vary considerably from steel to steel—but those given above will probably be about the average of those obtained in practice, and will in any event be within  $\pm 25^{\circ}$  F. On the other hand, the Ar1 temperatures given are liable to an even greater variation, as the maximum temperature attained in heating, the length of time occupied in both heating and cooling, the effect of the higher carbon contents, and many other experimental factors, all tend to change the position of the Ar1 range.

From these figures, and from the critical range diagram given for 3 per cent. nickel steels, it will be observed that the hardening of

nickel steels may be carried out at temperatures considerably lower than those required by the corresponding straight carbon steels.

**The Eutectoid for Nickel Steels.**—The effect of additional nickel, or at least up to 7 per cent., is to reduce the eutectoid carbon ratio below that of the 0.9 value for straight carbon steels. That is, a nickel steel with 3 per cent. nickel will be saturated, having neither excess ferrite nor excess cementite (on slow cooling), at about 0.75 to 0.8 per cent. carbon; while in 7 per cent. nickel steel the eutectoid ratio appears to be about 0.6 per cent. carbon. This fact is of great importance in case-hardening work, in that it not only permits of a shorter duration of the carburization in order to obtain the maximum carbon concentration necessary in the case, but also reduces the carbon content over which it is likely that enfoliation may occur.

**Heat Treatment of Pearlitic Nickel Steels.**—The heat treatment of pearlitic nickel steels presents some very interesting phenomena which are quite distinctive from ordinary straight carbon steels. One would naturally assume that the treatment of pearlitic nickel steels would be carried out in an analogous manner to that of the ordinary carbon steels—that is, the quenching should be done at a temperature slightly in excess of the upper critical range, provided that the duration of heating at the maximum temperature has been sufficient to effect the entire solution of the previous components, together with their diffusion and the equalization of the steel as a whole. Similarly, as in carbon steels, we would assume that we might replace the length of heating at the proper quenching temperature by a higher temperature in order more quickly to effect the equalization of the steel; provided, however, that this new and more elevated temperature shall not produce too great a deterioration in the metal through increase in grain-size, etc.—or that this higher quenching is followed by a quenching at the proper temperature. In straight carbon steels the change of structure by heating slightly above the upper critical range takes place quickly as a general rule; and the coarsening or embrittling of the steel also occurs rapidly when higher temperatures are used. The influence of nickel in the steel, however, often necessitates a modification, or permits a simplification, of these general principles, both in regard to the temperature of quenching and the length of heating.

In the first place, the addition of nickel appears to make the solution of the ferrite or cementite and the equalization of the steel as a whole take place more slowly than in the ordinary carbon



steels. Thus, if we take a steel containing some 4 or 5 per cent. nickel, and a mild or medium carbon content, and quench it after a normal heating at a temperature some 50° F. over the critical range, the transformation is often incomplete and the martensite not uniformly distributed nor equalized.

In such an event, which is usually characteristic of nickel steel which has either undergone a more or less severe elaboration or working, or has been finished at too low a temperature, or has been subjected to a prolonged heating at some high temperature, there are then four methods of procedure available:

- (1) Prolonged heating at the proper quenching temperature to effect the necessary transformation, followed by quenching;
- (2) Heating to a higher temperature than in (1), and quenching;
- (3) Heating to the higher temperature, cooling to a temperature a little above the Ar temperature, and then quenching;
- (4) Quenching, or air cooling, from the higher temperature, followed by a normal reheating to a temperature slightly in excess of the Ac range, and quenching.

These propositions at once evoke a discussion of further characteristics which the presence of nickel involves.

If an ordinary carbon steel be heated for a considerable duration of time at a temperature even slightly over the critical range, the grain-size will begin to increase, with a corresponding decrease in both the static and dynamic strength of the material. On the other hand, if a nickel steel be subjected to a length and temperature of heating equivalent to that of the carbon steel, the pearlite and ferrite grains will remain (after slow cooling) considerably finer, more uniformly distributed, and much more subdivided than the carbon steel. This characteristic permits the greater duration of heating as required under the first proposition, without any perceptible deterioration such as would be noticeable in a straight carbon steel with the same prolonged heating. However, such treatment—when required—is disadvantageous from the commercial standpoint, as it decreases the capacity of the heat treatment plant, with a corresponding increase in the cost of production.

Again, the increased brittleness due to a more or less prolonged heating at temperatures in excess of the upper critical range is considerably less for nickel steels than for ordinary carbon steels. This

fact is well illustrated by the following results upon a straight carbon steel in comparison with a 2 per cent. nickel steel of the same carbon content, taken from a *mémoire*<sup>1</sup> by Guillet:

Length of Heating at 1830° F.	Resistance to Shock.	
	Ordinary extra-soft steel.	Extra-soft steel with 2 per cent nickel.
Normal heating.....	20 kgms.	60 kgms. (not broken)
Four hours.....	4.5 kgms.	60 kgms. (not broken)
Six hours.....	4.0 kgms.	60 kgms. (not broken)

If, in order to obtain the full equalization of the steel and also to avoid a prolonged heating at the lower and theoretic temperature, it shall be necessary to heat and quench from a higher temperature, such operation may be undertaken without that fear of greatly increasing the brittleness which would most probably occur in a straight carbon steel.

Although it is granted that a heating to this high temperature may be necessary, a quenching from this same high temperature would not be entirely logical if this were to be the only quenching, and also if viewed from the standpoint of the best product. In such high temperature quenchings there is the ever-present danger of cracking and warping. Further, it is a generally admitted fact that no change in the molecular arrangement of the steel occurs in cooling such a steel until the upper critical range on cooling (Ar<sub>3</sub>) is reached. Assuming this to be true, we may then modify the previous treatment (proposition 2) by first cooling the steel—after heating to the high temperature—to a temperature slightly above that of the Ar<sub>3</sub> range, and then quench, as stated under proposition 3. This treatment will retain all the benefits which may accrue from the original high-temperature heating, but at the same time will diminish to a considerable degree the dangers of cracking and warping. And as the critical ranges on cooling in nickel steels are even further below those of the Ac ranges in comparison with straight carbon steels, this quenching temperature will be reasonably low.

Objections which may be offered to this method are that the quenching from just over the Ar range may not give the maximum

<sup>1</sup> M. L. Guillet, "Traitements thermiques des aciers speciaux," *Rev. de Met.*, July, 1910.



hardening effect unless the quenching temperature has been gauged just rightly, or if the carbon content is low. The first objection may be overcome by suitable temperature control; if the quenching temperature should fall too low, the difference in the hardening effect, for forgings or full-heat treated work, may be later corrected by using a lower toughening or drawing temperature. By the use of exact methods, such as one furnace maintained at the high temperature, and then another furnace (into which the steel may be subsequently placed) maintained at the temperature a little over the Ar range, the first objection may be entirely cleared away. The second objection may also be at once overruled by the fact that the treatment of the low-carbon steels is generally limited in commercial work to the obtaining of a suitable toughness and absence of brittleness (regeneration), and that it is usually not desired to obtain the maximum hardness.

In brief, it does not matter whether the same mechanical properties in a pull test are obtained by a quenching made at a very high temperature, or by a quenching at a lower temperature following the return. As these results in the mechanical properties are practically the same, the treatment under proposition 3, as compared with Number 2, is always more advantageous from the point of view of non-brittleness and probably also from the point of view of the strength of the piece.

The most serious objection to the treatment in either (2) or (3), however, is the increase in brittleness which is liable to occur if the high temperature heating is unduly prolonged. Although the presence of nickel tends to diminish such a condition, the effect of high heating is always towards the increase in grain-size, and coarse martensite generally corresponds to a diminution in the strength of the steel. Assuming that a temperature considerably in excess of the upper critical range is mandatory, any ill effects resulting therefrom may be entirely overcome by a double heating and cooling, and yet also retaining the benefits of such high temperature heating. That is, by cooling the steel—but not quenching, unless the original structure is very bad indeed; or unless the most perfect structure is desired—from the high temperature to a temperature under that of the A<sub>1</sub> range, in order to impress the effect of the high temperature upon the steel, followed by a reheating to a temperature slightly in excess of the upper critical range, and then quenching. Such a hardening treatment, either with air cooling and a subsequent single quenching, or with a double quenching,



is the best, although the most expensive. As this method has been discussed in its relation to carbon steels, and as its influence is approximately the same with pearlitic nickel steels, it will not be necessary to dwell further upon it.

In general, the treatments (for the best quenching effect) given under (1), (2) and (3) will suffice for ordinary commercial practice, but with the preference given to (1) or (3). That under (4) is best if the higher cost is permissible.

Moreover, it should be borne in mind that, in perhaps even a majority of cases, the regular and normal quenching from a temperature slightly in excess of the upper critical range ( $Ac_3$ ), after a thorough and uniform heating at that temperature, will generally suffice—and especially for small work. But in order more fully to explain the difficulties which are sometimes met with in the treatment of nickel steels, the author has entered into the foregoing explanations. As a safe and general fundamental principle, repeatedly urged, it is always advisable to quench from the lowest temperature which will give the desired results.

The tempering and toughening of pearlitic nickel steels is carried out exactly as with straight carbon steels, previously explained, and is dealt with in more detail later on in the chapter.

#### CARBURIZATION OF NICKEL STEELS

The general principles of the carburization of nickel steels are similar to those which apply to straight carbon steels, and should not require repetition. There are, however, certain peculiarities, presenting both advantages and disadvantages, which should be mentioned.

(1) Nickel steels show less susceptibility to brittleness due to prolonged heating at the high temperatures often used in carburization than do the corresponding carbon steels. This important fact not only gives a steel better able to withstand shock, but also gives a well-defined means of simplifying the subsequent heat treatment if desired. Such advantages may be readily obtained by the addition of even 2 per cent. of nickel, and largely compensate for the slightly higher cost.

(2) The variations in the concentration of the carbon in the carburized zones are more gradual and uniform in nickel steels than in carbon steels. This better distribution of the carbon therefore tends towards the prevention of a distinct line of demarkation between the different zones, and thus to eliminate the chipping and

flaking off of the case. Similarly, the phenomenon of "liquation,"—a principal factor in such enfoliation—is less marked, under equal conditions, in nickel steels than in carbon steels.

(3) Although it is true that carburization proceeds with greater slowness with some solid carburizing compounds, referring to their use with nickel steels with less than say 3.5 per cent. nickel, the use of a mixed cement (carbon monoxide plus carbon) will effect a carburization with a rapidity equal to that with ordinary carbon steels.

(4) Under the same conditions, the depth of penetration of the carburized zone for a given time, using a mixed cement, is even slightly higher for nickel steels than for carbon steels.

(5) The lesser hardness which, with the same treatment, is possessed by the carburized zones in nickel steel as compared with the carburized zones in carbon steels under identical conditions, is due not only to the different effects of different quenchings, but also to the smaller concentration (especially for less than 3 per cent. nickel) of carbon in the carburized zones. This disadvantage may be eliminated by raising the carbon in the carburized zone by a suitable change in the conduct of the carburization.

(6) When the nickel content exceeds 3 per cent. the maximum concentration of the carbon in the carburized zones decreases with an increase in the percentage of nickel contained in the steel. The following table, from Giolitti,<sup>1</sup> contains data relative to the maximum concentration reached by the carbon in the carburized zones when carburizing, under various conditions, steels with varying nickel contents:

Condition of Carburization.	Nickel Content.				
	2%	3%	5%	25%	30%
Carbon monoxide:					
5 hours at 1740° F.....		0.38	0.23	.....	0.15
5 hours at 1920° F.....		0.35	0.35	.....	0.17
Ethylene:					
5 hours at 1740° F.....	1.12	.....	0.93	.....	0.39
5 hours at 1920° F.....	.....	1.53	1.23	0.84	0.63
Mixed cement:					
2 hours at 1830° F.....	0.70	.....	0.70	.....	0.67
5 hours at 1830° F.....	1.12	.....	0.80	0.64	
5 hours at 1920° F.....	0.83	.....	0.73	0.59	
2 hours at 2010° F.....	0.92	.....	0.74	.....	0.40
5 hours at 2010° F.....	1.07	.....	0.83	0.73	

<sup>1</sup> F. Giolitti, "The Cementation of Iron and Steel."

(7) By employing a nickel steel of the proper nickel content, and carburizing in such a manner as to attain a definite maximum carbon concentration in the case, a steel characterized by a tough core and a martensitic structure in the case may be obtained *without subsequent quenching*. The approximate maximum carbon concentration in the case which it is necessary to obtain for steels with definite percentages of nickel in order to produce a martensitic structure without quenching, may be given about as follows:

Per cent. Nickel.	Per cent. Carbon.	Per cent. Nickel.	Per cent. Carbon.
2	1.50	5	0.95
3	1.30	6	0.85
4	1.10	7	0.75

Such methods eliminate the necessity for subsequent heat treatment, if so desired, and effect corresponding reductions in the cost of the process, besides obviating, in a large measure, such important factors as warping, grinding, etc. Further, by extending the carburization so as to reach a maximum of 1.5 per cent. carbon at the periphery, for steels containing 5 to 7 per cent. nickel, there can also be obtained a superficial layer, superimposed upon the martensitic zone, containing austenite, which easily admits of polishing without loss.

(8) The lower temperatures at which the critical ranges are located, in the pearlitic nickel steels, permit a lower temperature to be used in case carburizing, which is an important factor in intricate or exact work.

#### THERMAL TREATMENT AFTER CARBURIZATION

In general, the thermal treatment of nickel steels, subsequent to case carburizing, may be classified according to the structure of the case after slow cooling from the temperature of carburization—that is, whether it is pearlitic or martensitic. Although this structure depends primarily upon the conduct of the carburization and the maximum carbon concentration thus obtained in the case, the procedure as practically carried out in commercial work will usually give (upon slow cooling after carburization) (1) a pearlitic structure in the case for steels with nickel contents under 4 per cent. and (2) a more or less martensitic case for steels with 4 to 7 per cent. nickel.



As explained in Chapter VII, the best treatment which can be given any case-carburized pearlitic steel is that involving a double quenching. Each quenching—for regeneration and for hardening—should be carried out at the most suitable temperature, and which is fixed by the transformation points of the core and case respectively. These treatments for nickel steels with 2 to 2½ and 3 to 3½ per cent. nickel are approximately as follows:

**Carburization.**—Carburize at the desired temperature, usually 1600° to 1750° F. Cool slowly in the carburizing material (assuming solid cements).

**Thermal Treatment.**—

Nickel Content, Per cent.	2 to 2½.		3 to 3½.	
	0.10 to 0.15	0.15 to 0.20	0.10 to 0.15	0.15 to 0.20
Regenerative quenching.....	(a) 1550–1600° or (b) 1600°	1500–1550° 1600°	1475–1525° 1600°	1450–1500° 1600°
Hardening quenching.....	1325–1375°	1325–1375°	1300–1350°	1300–1350°

The steel may be removed from the quenching bath as soon as it loses its red color during the regenerative quenching, and immediately reheated for the second quenching. Practice differs as to the temperature to be used for the regenerative quenching, some preferring to quench from a temperature slightly above the Ac3 range, as under (a), while others prefer to use the higher temperature (b). The reasons for these have been discussed in previous sections.

On the other hand, for 2 per cent. nickel steels, Guillet recommends temperatures distinctly higher than those given above—which probably coincide with the best American practice—for the regenerative quenching, and which he gives as follows:

Regenerative quenching.....	1760° to 1800°
Hardening quenching.....	1365° to 1420°

The hardening quenching should be conducted at the lowest possible temperature at which the metal of the case will become glass-hard. In many instances it will be found that temperatures somewhat lower than those given in the above table can be used. For

example, the critical curve given in Fig. 161 for a steel with 0.13 per cent. carbon, 0.49 per cent. manganese and 3.35 per cent. nickel, shows the  $Ac_1$  range to be about  $1250^{\circ}$  F., so that a temperature under  $1300^{\circ}$  to  $1350^{\circ}$  might be used effectively for the hardening quenching.

The effect of different treatments upon Guillet's 2 per cent. nickel steel in its resistance to shock is shown in the following table:

Treatment.	Resistance to Shock.
Steel with 2 per cent. nickel and 0.1 per cent. carbon:	
Heated to $1700^{\circ}$ F. and air cooled.....	33.4 kgms.
Quenched in water from $1700^{\circ}$ F.....	34.5
Same steel cemented at $1830^{\circ}$ F. for 1.2 mm.:	
Slow cooled.....	31.0
Quenched in water from $1830^{\circ}$ F.....	33.5
Double-quenched in water, $1830^{\circ}$ and $1380^{\circ}$ .....	36.0
Quenched in water from $1380^{\circ}$ F.....	32.0

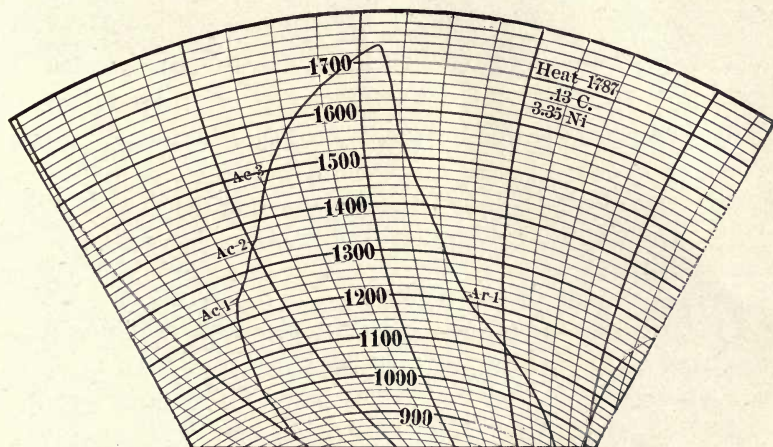


FIG. 161.—Critical Range Diagram.

**Simplified Thermal Treatments after Carburization.**—On account of the fact that the brittleness of the core (with nickel steels) is not greatly increased by the heating during carburization if the temperature of that operation is not too high, and as the  $Ac_3$  range of the ordinary nickel steels is considerably lower than that of the corresponding straight carbon steel, it makes it possible, as we have seen, to effect a regenerative quenching at a temperature in the neighborhood of  $1500^{\circ}$ - $1550^{\circ}$  F. Further, as the nickel steel case can be



hardened at a temperature considerably above the normal  $A_{c1}$  without losing too much of its hardness or increasing too largely in brittleness, it follows that, in many instances, the regenerative quenching may also serve as a hardening quenching. This permits the simplification of the treatment to a single quenching for nickel steels, unless the piece is to be subjected to exceptional stress. The practical usefulness of this method is obvious.

It is evident, however, that the double quenching will always give considerably better results for both core and case. This is particularly shown in the depth and degree of hardness obtained by the lower quenching over the higher quenching temperature by the following experiments by Guillet on 2 per cent. nickel steels:

Treatment.	Shore Hardness Numbers.		
	Maximum.	Minimum.	Mean.
Cemented pieces, not quenched. . . . .	40	39	39.37
Cemented pieces, quenched from $1830^{\circ}$ F.	84	69	78.05
Cemented pieces, quenched from $1380^{\circ}$ F.	88	85	86.56

**Case Hardening by Air Cooling.**—Again, the case-hardening process may be even further simplified by the use of nickel steels with 3.5 per cent. of nickel, or more, and conducting the carburization in such a manner as will produce a maximum carbon content in the case, which will give a martensitic structure on air cooling from the temperature of carburization. An example of this is shown in Figs. 162 and 163, representing a case-carburized steel with an initial carbon content of 0.176 per cent., with 3.44 per cent. nickel; the steel was then air cooled directly after carburization. The thickness of the martensitic zone is about 0.5 mm. Under the lower magnification (Fig. 163) a solid troostitic band is seen to separate the martensite and the sorbito-pearlite portions. The principal advantage which this method presents consists of its great simplicity, and also in the fact that it permits the avoidance of deformation which so often accompanies any quenching operation. Nickel steels which are martensitic after air cooling may be troostitic, sorbitic, or even pearlitic after very slow cooling in the furnace, while they may be austenitic on water quenching.

**Case Hardening 5 to 7 Per Cent. Nickel Steels.**—Advancing another step and using nickel steels with 5 to 7 per cent. nickel, we find that the ordinary carburization and subsequent slow cooling



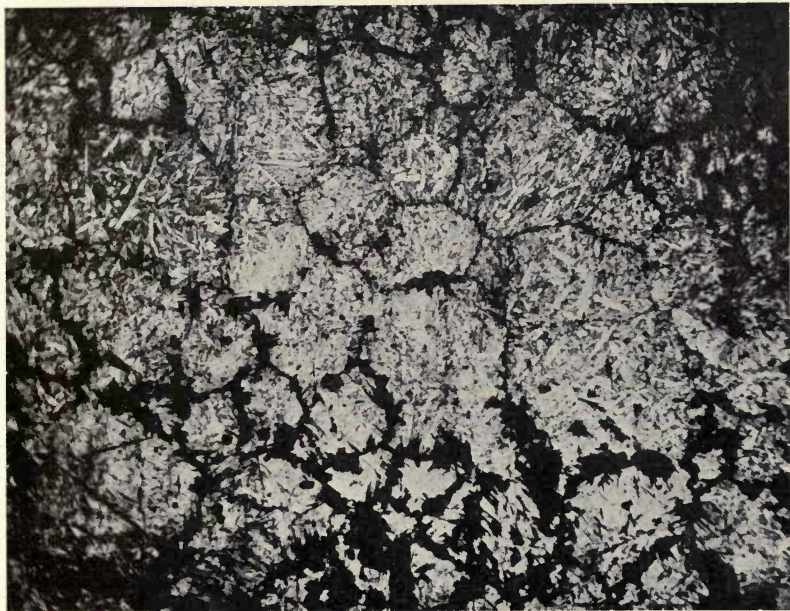


FIG. 162.—Nickel Steel. Nickel, 3.44 per cent. Carbon, 0.176 per cent. Case Carburized and Air Cooled.  $\times 100$ . (Sauveur and Reinhardt.)

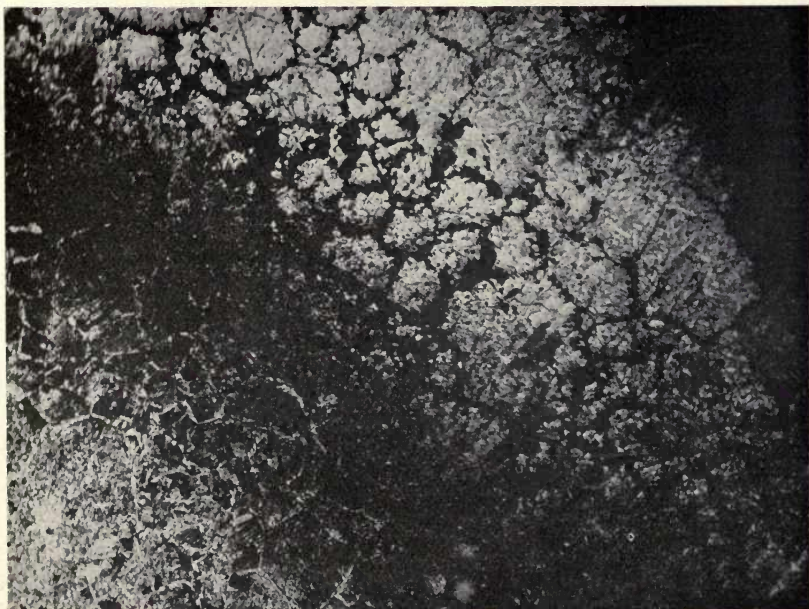


FIG. 163.—Same Steel and Treatment as in Fig. 162.  $\times 50$ . (Sauveur and Reinhardt.)

will produce a case with characteristics varying over a wide range, dependent upon the nickel-carbon ratio in the case. In other words, the transformation range of the metal of the case on cooling may be even further reduced below that of the previous example, giving either a martensitic or martensite-austenitic structure upon slow cooling. Therefore, when it is not required to produce an extremely tough core, nor to obtain extreme hardness in the case, the carburized pieces with 5 to 7 per cent. nickel may simply be allowed to cool slowly in the carburizing mixture after carburization.

The use of the method just indicated, however, has its disadvantages. The following table shows the results of scleroscope hardness tests made by Guillet on a steel containing 7 per cent. nickel and 0.12 per cent. carbon, carburized to a depth of 0.1 mm., but not quenched:

Treatment and Tests.	Shore Hardness Numbers.		
	Mean.	Maximum.	Minimum.
Test made on the surface.....	18.5	21	17
Test made at a depth of 0.2 mm.....	26.5	27	26
Test made at a depth of 0.4 mm.....	24.5	25	24
Test made at a depth of 0.6 mm.....	20.2	20	21

From this particular instance it will be seen that the surface zone is partly austenitic, so that a very great hardness is not obtained.

In the second place, it is evident that the core of the piece thus treated has not been regenerated, although, as we have said before, nickel steel does not have the maximum brittleness which a straight carbon steel would have under the same conditions of cooling.

The structure of a steel containing 4.86 per cent. nickel and 0.115 per cent. carbon, intensely carburized, and air cooled, is shown in Fig. 164. This photomicrograph shows that the effect of such treatment is to produce a case which is largely austenitic.

The best practice, however, both American and foreign, specifies the use of a double-quench treatment subsequent to a *mild carburization*, and using a soft steel with 4.5 to 6 per cent. nickel. Such steels have many peculiar advantages: the carburization may be conducted at a moderate temperature; a maximum carbon content in the carburized zone of only about 0.45 to 0.6 per cent. is necessary to produce a glass-hard surface on *oil quenching*; and the core becomes exceedingly strong, as well as tough and non-brittle. From



these facts it is evident that the lowering of the maximum carbon concentration to a percentage not exceeding that of the eutectoid ratio will almost entirely eliminate the danger of chipping and flaking. The use of moderate temperatures for carburization and of oil for quenching decreases the liability to warping and fracture. The physical characteristics of the carburized zone after the second oil quenching, the steel of the case having an approximate chemical

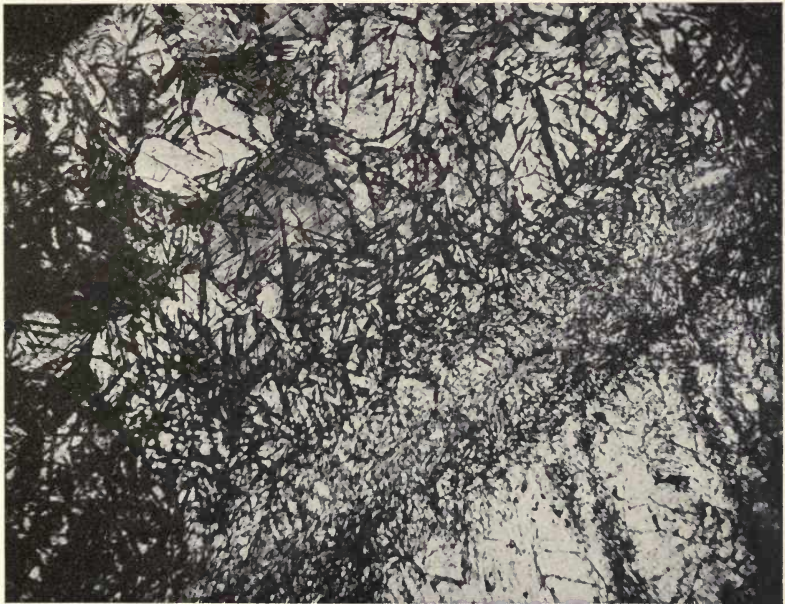


FIG. 164.—Nickel Steel. Nickel, 4.86 per cent. Carbon, 0.115 per cent. Case Carburized and Air Cooled.  $\times 100$ , (Sauveur and Reinhardt.)

composition of 0.45 per cent. carbon and 5.0 per cent. nickel, will be approximately:

Tensile strength, lbs. per sq. in. ....	260,000
Elastic limit, lbs. per sq. in. ....	250,000
Elongation in 2 ins., per cent. ....	2
Reduction of area, per cent. ....	5
Brinell hardness. ....	490
Scleroscope hardness. ....	74



The following physical results taken from the core of a double-quenched steel analyzing:

Carbon.....	0.105
Manganese.....	0.43
Phosphorus.....	0.014
Sulphur.....	0.030
Silicon.....	0.11
Nickel.....	5.0

show that the core will have great strength, high ductility (from the reduction of area), and very slight brittleness (as shown by the shock test):

Tensile strength, lbs. per sq. in.....	200,000
Elastic limit, lbs. per sq. in.....	170,000
Elongation in 2 ins., per cent.....	12
Reduction of area, per cent.....	54
Resistance to shock.....	75
Brinell hardness.....	295

The same steel, having an upper critical range of 1425° F., and annealed at 1475° F., gave:

Tensile strength, pounds per square inch....	90,600
Elastic limit, pounds per square inch.....	60,160
Elongation in 2 ins., per cent.....	20
Reduction of area per cut.....	60.5
Resistance to shock.....	116
Brinell hardness.....	179

The regenerative quenching for these steels may be carried out either at a temperature slightly in excess of the upper critical range—or at about 1475° F., or, in order to more fully equalize and effect the regeneration of the core, at some higher temperature, such as 1600° F. The hardening quenching temperature should be slightly over the Ac range of the case, or approximately 1275° to 1325° F. Oil may be used for both quenchings. For the characteristic French steel containing about 6 per cent. nickel Guillet recommends the temperatures of 1560° and 1250° F. respectively for the double quenching.

### 3.5 PER CENT. NICKEL STEEL

We have previously discussed some of the factors which enter into the quenching of nickel steels in general. Whether or not it

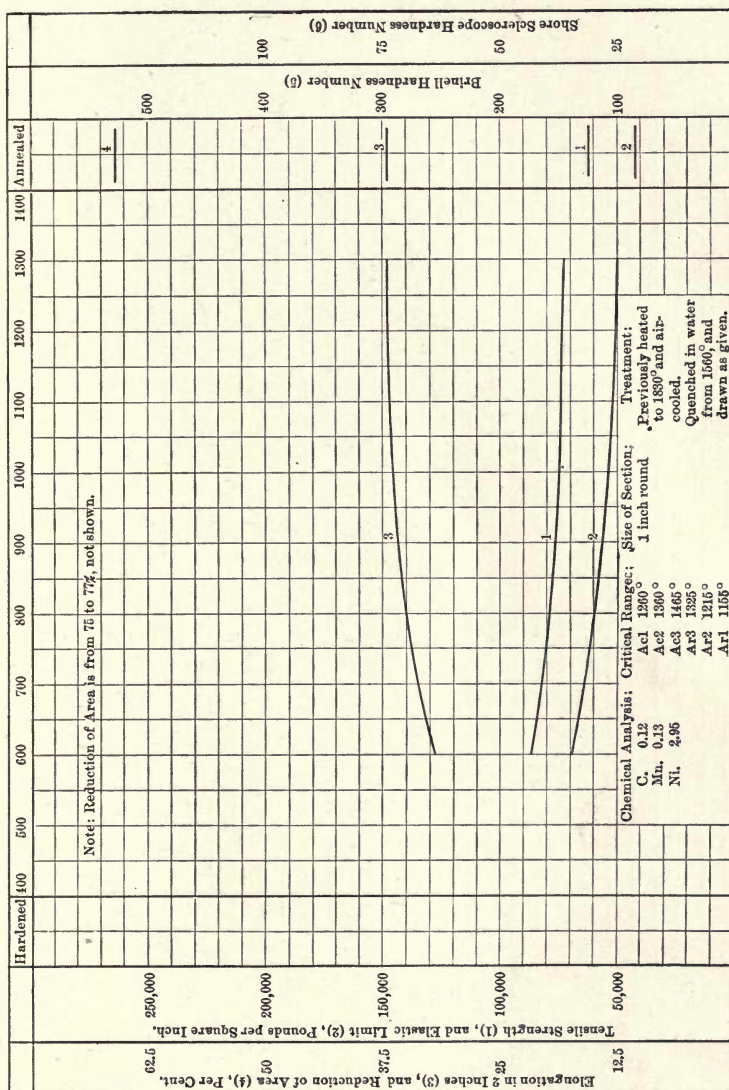


Fig. 165.—Normal Characteristics of Very Low Carbon, 3 per cent. Nickel Steel.

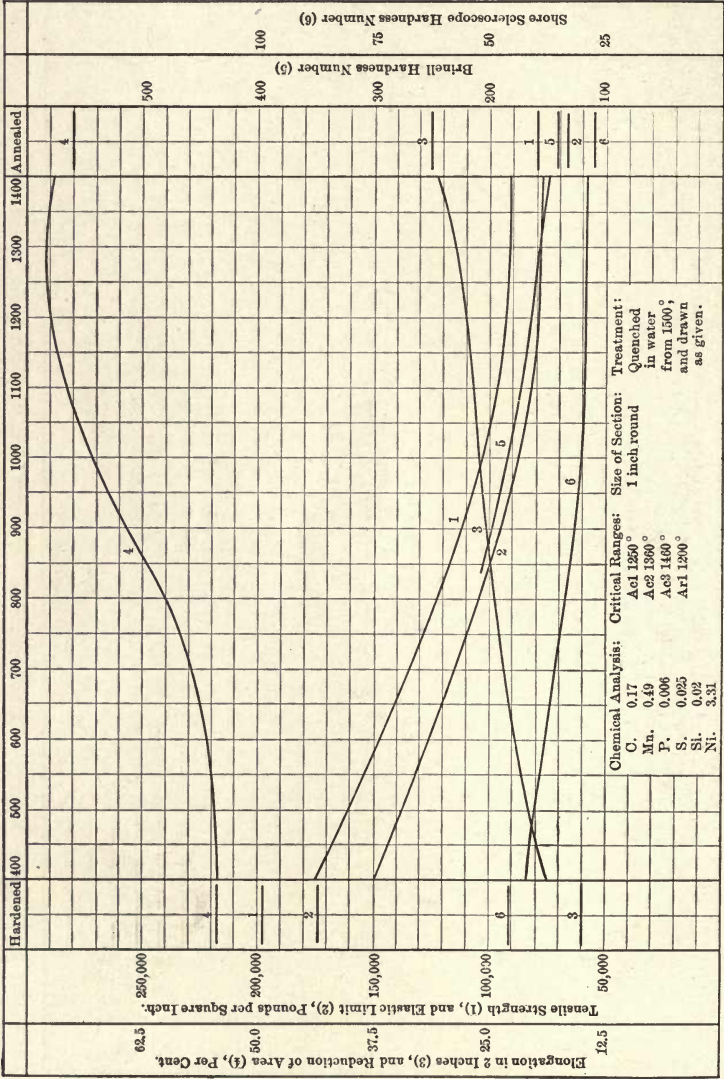


Fig. 166.—Normal Characteristics of Low Carbon, 3½ per cent. Nickel Steel.



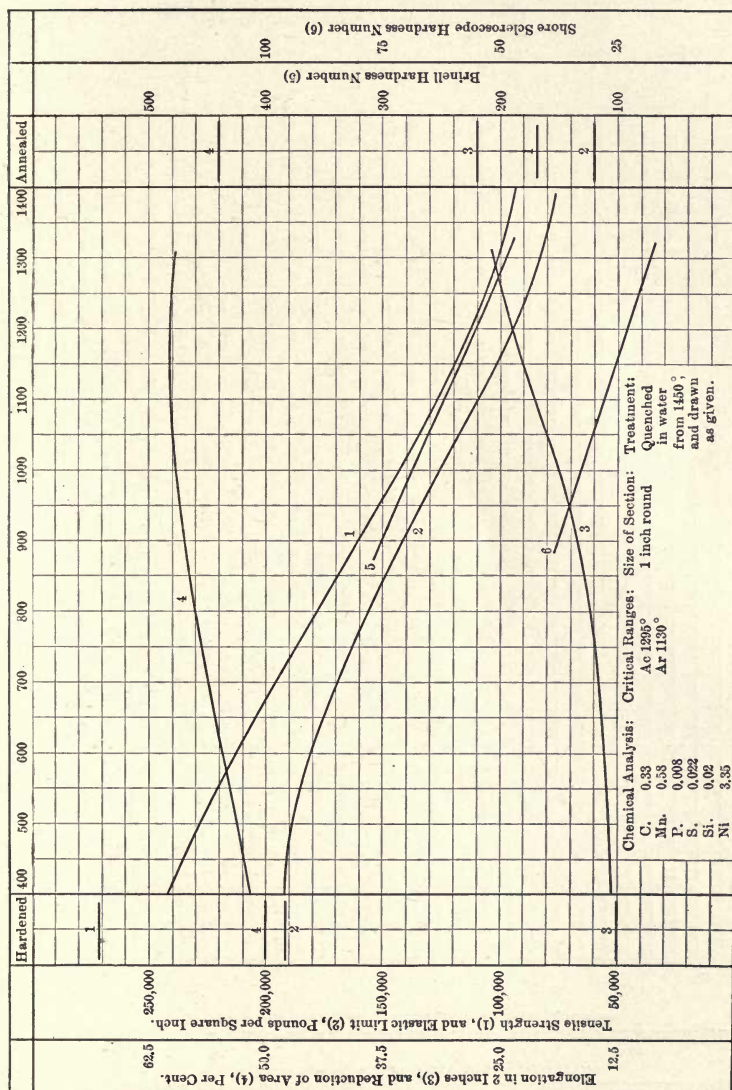


Fig. 167.—Normal Characteristics of 0.30 Carbon, 3½ per cent. Nickel Steel.

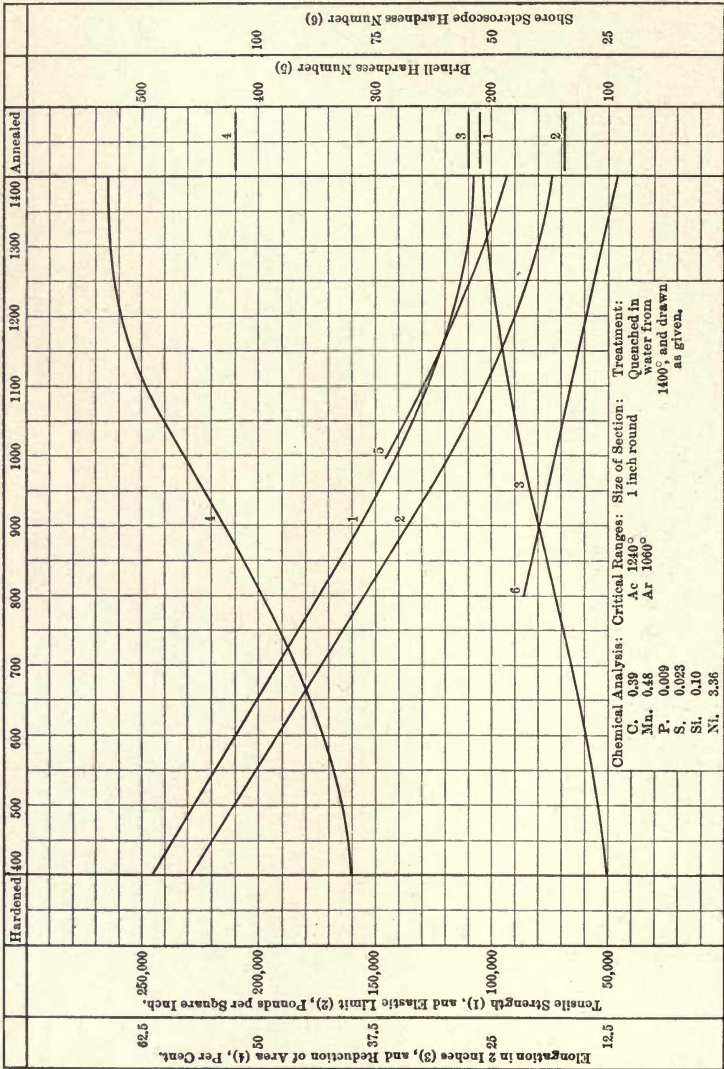


FIG. 168.—Normal Characteristics of 0.40 Carbon, 3½ per cent. Nickel Steel.

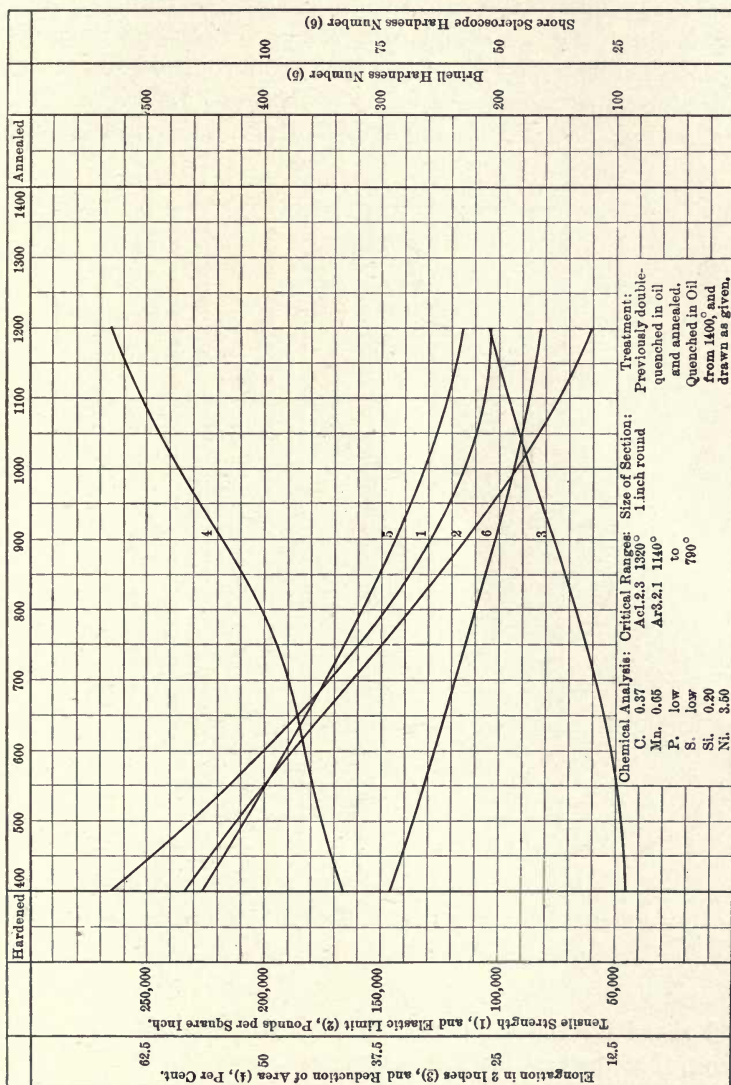


Fig. 169.—Normal Characteristics of 0.40 Carbon, 3½ per cent. Nickel Steel.



may be necessary to use a temperature considerably in excess of the upper critical range for hardening will depend upon the condition of the steel as it comes to the heat-treatment plant; in many cases the normal heating and quenching will suffice for general purposes. The normal hardening temperatures for 3 to 3½ per cent. nickel steel may be approximately determined by reference to the critical range diagram in Fig. 160, and by adding 50 to 100 degrees to the upper

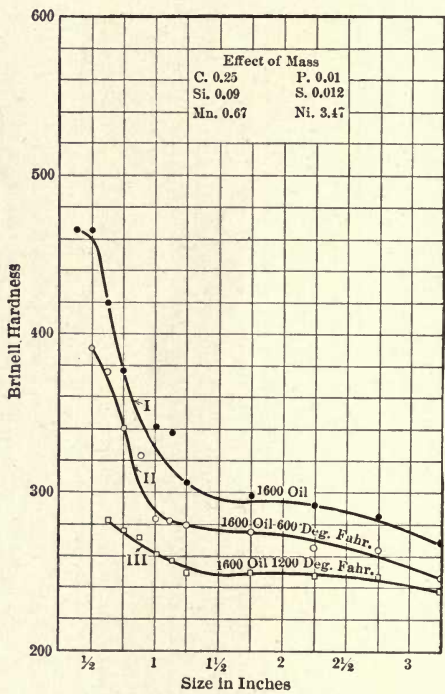


FIG. 170.—Effect of Mass upon the Hardness of Nickel Steel, Oil Treated. (Matthews & Stagg.)

critical range for the given carbon content. It should be noted, however, that the best hardening temperature should be determined experimentally, whenever possible, for the particular stock to be treated, since the method of manufacture, elaboration, size of section, and various other factors all influence such temperature.

The normal characteristics obtained by the heat treatment of 1-in. nickel steel rounds are shown in the charts of Figs. 165 to 169. It

should be remembered that these figures, although they have been carefully checked up with other results as far as is possible, are experimental figures, and should be used with discretion. In other words, ordinary commercial heat-treatment practice involves so many variables, and especially the "personal equation," that it should not be expected that these results will be duplicated in every instance.

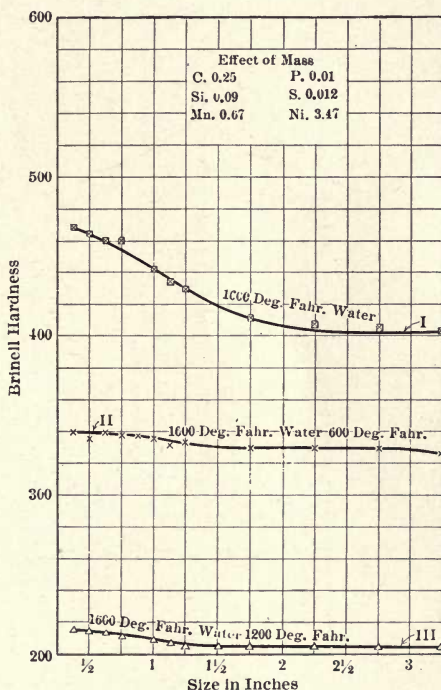


FIG. 171.—Effect of Mass upon the Hardness of Nickel Steel, Water Quenched. (Matthews & Stagg.)

Again, these results represent the treatment of 1-in. round sections—so that while such results might be duplicated in practice with sections up to 1½ ins. in diameter, further increase in the size of section will inevitably lower the physical test results to be obtained under the same treatment. The influence of mass upon the Brinell hardness is shown in Figs. 170 and 171.

On the other hand, the normal characteristics for annealed 3½ per cent. nickel steel, as given in the diagram in Fig. 172, represent the

average results which are, and should be, obtained in commercial practice in the annealing of the more common and larger sections of nickel steel. They represent, moreover, the minimum requirements which are characteristic of many existing steel specifications for  $3\frac{1}{2}$  per cent. nickel steel, annealed, for such uses as engine forgings,

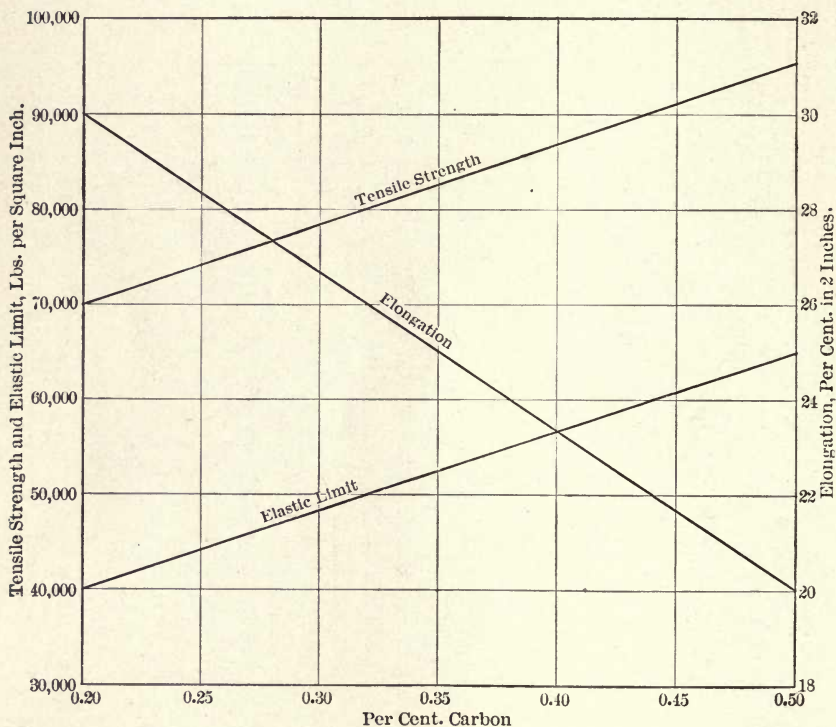


FIG. 172.—Normal Characteristics of Annealed 3.5 per cent. Nickel Steel.  
Large-size Sections of Forgings. Manganese Approx. 0.6 per cent.

ordnance forgings, rolled slabs and billets, etc., both for Government and commercial uses.

Similarly, the following physical results for heat-treated work (quenched and toughened) have been taken from various specifications in order to show the minimum results which may be expected in commercial practice. The manganese requirements are approximately 0.50 to 0.70 per cent., and the nickel content not less than 3.25 per cent.



## 3½ PER CENT. NICKEL STEEL SPECIFICATIONS

Carbon.	Section or Use	Treatment.	Tensile Strength.	Elastic Limit.	Elongation.	Red. of Area.
0.15-0.20	Core of treated gear.....	Case hardened....	100,000	80,000	14	44
0.15-0.20	Teeth of treated gear.....	Case hardened....	160,000	160,000	0	0
0.15	S. A. E. spec.....	Annealed.....	.....	35,000-45,000	35-25	65-45
0.15	S. A. E. spec.....	Heat treated.....	.....	40,000-80,000	35-15	65-40
0.20	S. A. E. spec.....	Annealed.....	.....	40,000-50,000	30-20	65-40
0.20	S. A. E. spec.....	Heat treated.....	.....	50,000-125,000	25-10	65-40
0.25	S. A. E. spec.....	Heat treated.....	.....	60,000-130,000	25-10	65-40
0.20-0.25	Auto shafts (French steel), spec.....	Annealed.....	70,000-82,000	43,000-51,000	25-20	
0.20-0.25	Auto shafts (French steel), spec.....	1475°/930°.....	108,000-132,000	82,000-109,000	14-11	
0.25	Medium forgings.....	As forged.....	70,000	45,000	25	60
0.30-0.40	1½ in. auto shafts, minimum spec.....	Heat treated.....	135,000	120,000	16½	50
0.30-0.40	Forgings, under 3½-in. dia. min. spec.	Heat treated.....	105,000	90,000	16	50
0.35 max.	Govt. spec., large forgings.....	Annealed.....	80,000	50,000	{ 25 (long.) 21 (trans.)	
0.35 max.	Govt. spec., large forgings.....	Oil treated.....	95,000	65,000	{ 21 (long.) 18 (trans.)	
0.30-0.40	S. A. E. spec.....	Annealed.....	.....	45,000-55,000	25-15	55-35
0.30-0.40	S. A. E. spec.....	Heat treated.....	.....	65,000-150,000	25-10	55-25
(0.40-0.50)	Isth. Canal Comm. spec., forgings...	Annealed.....	85,000-100,000	55,000	17½ min.	(40)
0.40-0.50	S. A. E. spec.....	Annealed.....	.....	55,000-70,000	25-15	50-30
0.40-0.50	S. A. E. spec.....	Heat treated.....	.....	70,000-200,000	20-5	55-15

The relation which the maximum size of section bears to the physical properties of steel is well illustrated by the following specification for Railway Motor Shafts—the steel to contain 3 to 4 per cent. nickel:

Max. Dia., Inches.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation, Per Cent. in 2 Ins.	Reduction of Area, PerCent.
3	95,000	65,000	21	50
6	90,000	60,000	22	50
10	85,000	55,000	24	45
20	80,000	45,000	25	45
over	80,000	45,000	24	40

The following equations connecting maximum strength, Brinell hardness number and scleroscope hardness number have been computed<sup>1</sup> from several hundred tests made with nickel steels of different carbon content and heat treated to bring out all possible physical properties:

$$(1) M = 0.71 B - 32.$$

$$(2) M = 3.5 S - 6.$$

$$(3) B = 5.0 S + 48.$$

$M$  = maximum strength in units of 1000 lbs. per sq. in.

$B$  = the Brinell hardness number.

$S$  = the scleroscope hardness number.

The maximum strength corresponding to different Brinell values as determined by equation (1) for these steels is as follows:

Brinell.	Maximum Strength, Lbs. per Sq. In.	Brinell.	Maximum Strength, Lbs. per Sq. In.
100	39,000	350	216,000
150	74,000	400	252,000
200	110,000	450	287,000
250	145,000	500	323,000
300	181,000	550	358,000

The maximum strength corresponding to different scleroscope values as determined by equation (2), and the corresponding Brin-

<sup>1</sup> R. R. Abbott, A. S. T. M., Vol. XV, Part II, 1915, p. 43 et seq.

ell numbers as determined by equation (3), for these steels, are as follows:

Scleroscope.	Maximum Strength, Lbs. per Sq. In.	Brinell.
20	64,000	148
30	99,000	198
40	134,000	248
50	169,000	298
60	204,000	348
70	239,000	398
80	274,000	448
90	309,000	498
100	344,000	548

#### 5 PER CENT. NICKEL STEEL

The use of nickel steel with the higher nickel content is now largely limited to case-hardening purposes, which we have previously described.

The physical results obtained from the treatment of 1-in. sections, containing 5 per cent. nickel and 0.33 and 0.43 per cent. carbon, are shown in the charts in Figs. 173 and 174 respectively.

#### HIGH-NICKEL STEELS

The high-nickel steels of 25 to 35 per cent. nickel are used principally for gas-engine valves and spindles, ignition and boiler tubes, and for other similar purposes. These nickel steels are extremely tough, dense, have a high resistance to shock, a low coefficient of expansion, and—in particular—are little subject to corrosion.

Their physical properties in the natural condition may be given as follows:

	25 to 28% Nickel (0.3 to 0.5% Carbon)	30 to 35% Nickel (average)
Tensile strength, lbs. per sq. in. . .	85,000 to 92,000	95,000
Elastic limit, lbs. per sq. in. . . . .	35,000 to 50,000	50,000
Elongation, per cent. in 2 ins. . . .	30 to 35	40
Reduction of area, per cent. . . . .	50 to 60	58

These steels do not respond to heat treatment, but may be annealed at about 1450° F. to facilitate machining, after which the



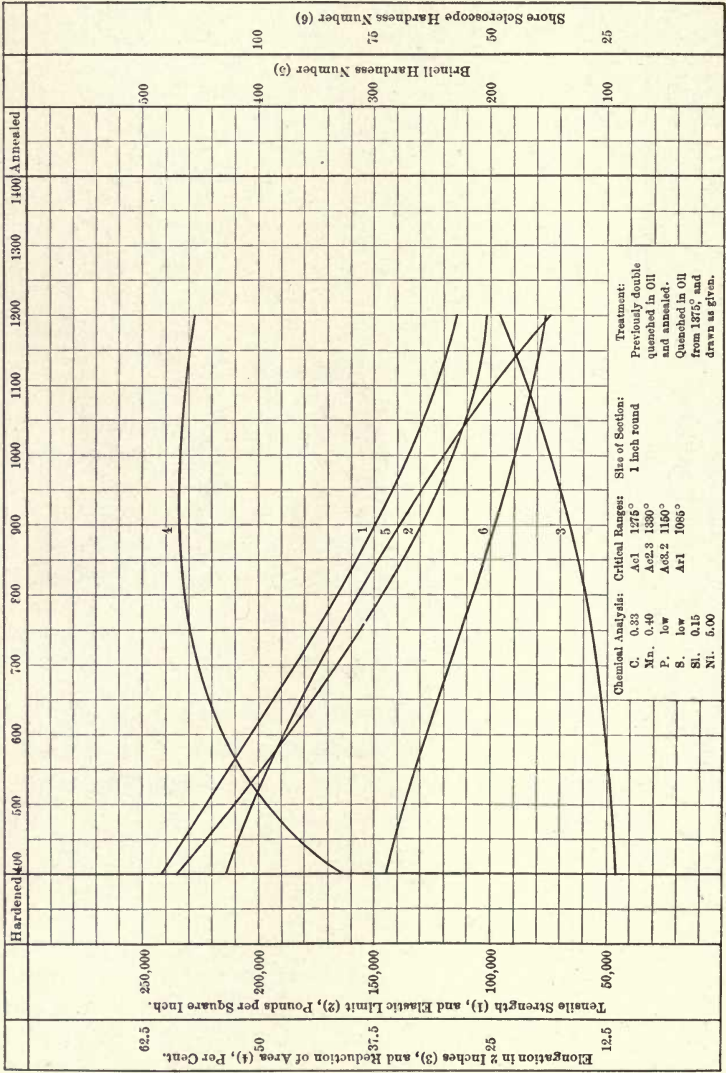


FIG. 173.—Normal Characteristics of 0.33 Carbon, 5 per cent. Nickel Steel, Heat Treated.

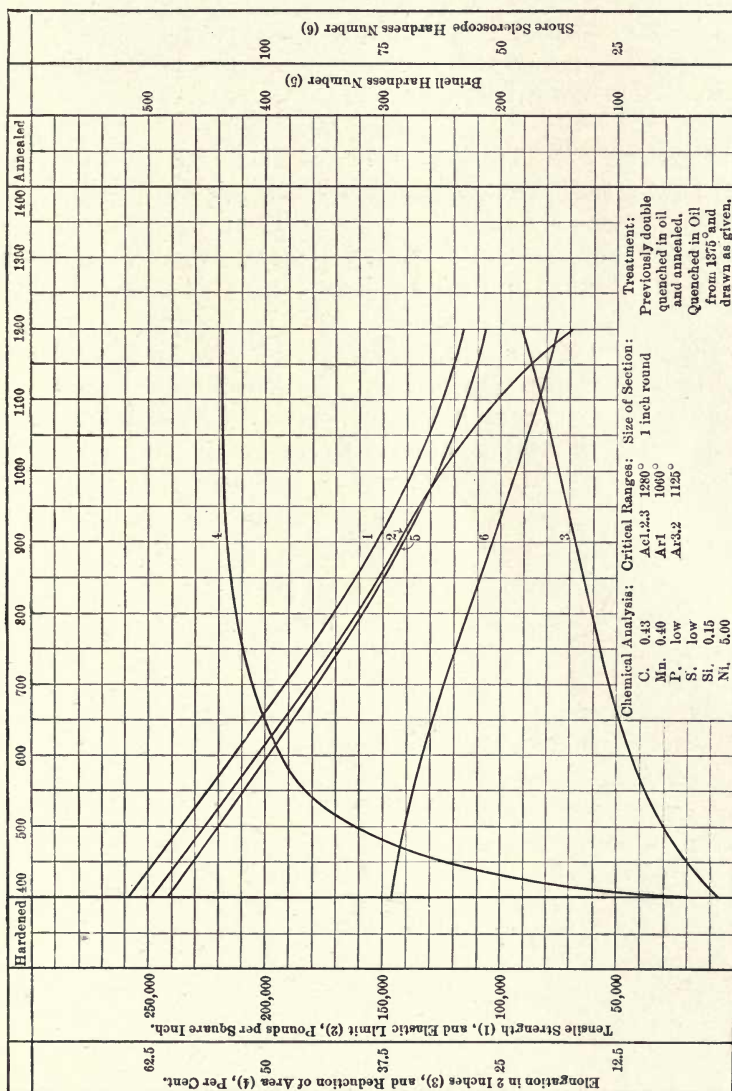


Fig. 174.—Normal Characteristics of 0.43 Carbon, 5 per cent. Nickel Steel, Heat Treated.

physical properties of the 30 to 35 per cent. nickel steels given above will average:

Tensile strength, lbs. per sq. in.....	85,000
Elongation, per cent. in 2 ins.....	30
Reduction of area, per cent .....	40

Nickel steels with 35 to 38 per cent. nickel and 0.3 to 0.5 per cent. carbon have a coefficient of expansion which is less than any metal known and amounts practically to zero. These alloys are used for various clock, geodetic and similar instruments for precise measurements. The physical properties of these steels are approximately:

Tensile strength, lbs. per sq. in.....	100,000 to 115,000
Elastic limit, lbs. per sq. in.....	64,000 to 78,000
Elongation, per cent. in 2 ins.....	35 to 25
Reduction of area, per cent.....	50



## CHAPTER XII

### CHROME STEELS

CHROME in steel has the characteristic function of opposing both the disintegration and reconstitution of cementite.<sup>1</sup> This is made noticeable by the changes in the critical ranges of the steel, as it makes them take place more slowly, that is, it has the tendency to raise the Ac range and to lower the Ar range. Chrome steels are therefore capable of greater hardness because rapid cooling is able more completely to prevent the decomposition of the austenite.<sup>2</sup> The greater hardness of chrome steels is also due to the presence of double carbides of chrome and iron in the steel in the hardened or slightly tempered condition. This additional mineral hardness is obtained without raising the brittleness to such a degree as does carbon. The degree of hardness is within certain limits dependent upon the carbon content, as chrome alone will not harden iron. Harbord<sup>3</sup> states that carbonless, or nearly carbonless, chrome steel does not harden when water quenched. Toughness is also conferred by the degree of fineness of the structure, which is a characteristic of chrome steels (similar to that of nickel), thus increasing the tensile strength and elastic limit without a noticeable loss of ductility. Thus we have that condition of "tough-hardness" which makes chrome steel so valuable in parts requiring great resistance to wear (abrasive action<sup>4</sup>). In regard to corrosion, Chappell<sup>5</sup> states that "in neutral corroding media the resistance offered to corrosion apparently rises with the percentage of chromium. This is particularly the case for salt water, and the employment of chromium steels in the construction of ships would appear to be fully justified on this ground alone.—The corrosion factor does not appear to be a purely additive quantity."

<sup>1</sup> Savoia, "Metallography" (trans.), p. 315.

<sup>2</sup> Stoughton, "Metallurgy of Steel," p. 407.

<sup>3</sup> Harbord, "Metallurgy of Steel," Vol. I, p. 390.

<sup>4</sup> See F. Robin, *Journal. Iron and Steel Inst.*, Vol. II, 1910.

<sup>5</sup> Chappell, *Journ. Iron and Steel Inst.*, 1912.

The influence of chrome towards increasing the brittleness of steel, especially upon prolonged heating at high temperatures in the case-hardening process, is shown in the following results of tests by Guillet:<sup>1</sup>

Treatment.	Resistance to Shock.	
	Chrome 0.70%. Carbon 0.05%.	Chrome 1.20%. Carbon 0.05%.
Annealed.....	32 kgms.	25 kgms.
Quenched.....	22	15
Heated for 4 hours at 1830° F.	5	5
After double quenching.....	26	20

### 0.5 PER CENT. CHROME STEELS

Low-chrome steels find many valuable uses and at only a slightly increased cost, since the usual charge by open-hearth steel manufacturers for 0.5 per cent. chrome steel is only about one or two dollars a ton over the "base price." One-half of one per cent. chrome raises the critical range on heating by about 25° to 35° F. over that of the corresponding straight carbon steel. As a leeway of at least 50° F. over the critical range is usually allowed for in hardening, these chrome steels may in general be hardened at the same temperature as for straight carbon steels of the same carbon content.

### 0.5 CHROME, LOW CARBON

For carbons up to about 0.35 per cent. the addition of this small amount of chrome confers practically no additional physical properties other than those which might be obtained by the use of a slightly higher carbon content in a straight carbon steel. On the other hand, for case-hardening purposes this small amount of chrome confers homogeneity, greater strength and wearing qualities, due to the much finer grain throughout after the double quenching, and to the presence of double carbides in the case. It should be remembered that chrome strengthens the cementitic element of the structure of steel, which in turn must depend upon the amount of pearlite; nickel, on the other hand, influences the ferrite constituent. Although both elements will tend to make the structure much finer,

<sup>1</sup> L. Guillet, "Trempe, recuit, revenu—"

it is evident that while nickel will have its greatest effect upon the lower carbon steels (those containing large amounts of ferrite), chrome will be of the most importance in the high carbons in which there is considerable cementite. Thus it is that although chrome in small amounts will be of little direct importance in ordinary heat-treated low-carbon steels, it will be of tremendous importance in any case-hardening operation which will produce a high-carbon case.

The addition of chrome probably increases the velocity of penetration of the carburization, under identical conditions, over that of the corresponding straight carbon steels. With greater amounts of chrome there is also the tendency toward a higher maximum carbon concentration than that obtained with carbon steels similarly carburized. The tendency to surface oxidation during carburization as a characteristic of chrome steels has been noted by several investigators; methods involving the use of mixed cements may be used, however, which will modify or even eliminate this action.

As chrome emphasizes the harmful effects of prolonged heating (opposite to the action of nickel), it is always necessary to double quench the steel; that is, a regenerative quenching as well as the usual hardening quenching. The greater surface hardness obtained by the use of chrome steels permits the use of oil for both quenchings, if desired, and thus tends to avoid deformation of the steel.

#### 0.50 CHROME—0.35 TO 0.50 CARBON

It has been the author's experience that with a carbon content up to say 0.50 per cent. carbon, the addition of a half per cent. chrome will give, after heat treatment, about 15 per cent. increase in tensile strength, 10 per cent. increase in elastic limit, with practically no loss in ductility, over straight carbon steels of the same carbon content. In the hardened condition it gives excellent service for wearing surfaces, such as the jaws of wrenches, small gears, etc. The tables on page 298 give test results obtained from open-hearth steels.

#### 0.50 CHROME, OVER 0.50 CARBON

With the increase in carbon the influence of chrome becomes even more marked, due to the increasing amounts of double carbide. The hardness increase is greater proportionally than the carbon increase. For well-bits and jars in the hardened condition this steel has no equal among the low-priced alloys or straight carbon steels.



For die blocks used in drop-forging work it does not seem quite to "hit the mark," apparently not having the requisite toughness to offset the brittleness, especially in the larger sections. With 0.70 to 0.80 per cent. carbon it makes an excellent chisel, while with 0.90 to 1.00 per cent. carbon and about 0.60 per cent manganese it gives even better results for pneumatic chipping chisels than do many varieties of high-speed steel. The Germans in particular have made great use of 0.5 per cent. chrome steels for tools, such as drills, saw-blades, knives, razors, files, and similar tools requiring a keen cutting edge. Further increase in hardness may also be obtained by the addition of silicon and manganese. The minimum hardening temperatures for the higher carbons should always be used to obtain the maximum effect of the chrome.

Treatment.	C.	Mn.	P.	S.	Si.	Cr.
1500° F. oil/1200° F.*	0.36	0.44	0.008	0.021	0.05	0.57
1500° F. oil/1300° F.*						
1500° F. oil/1300° F.*						
As rolled, 4"X4" billet...	0.40	0.50	0.015	0.025	.....	0.55
1460° F. water/1000*..	0.47	0.60	0.006	0.025	0.108	0.51
1460° F. water/1100*..						
1460° F. water/1200*..						
1460° F. water/1300*..						
8" round as hammered ..	0.47	0.55	0.015	0.029	.....	0.57

Treatment.	Tensile Strength, Lbs. per Sq. in.	Elastic Limit, Lbs. per Sq. in.	Elongation, Per cent. in 2 Ins.	Reduction of Area, Per cent.	Brinell Hardness.	Scleroscope Hardness.
1500° F. oil/1200° F.*	103,200	76,000	27.0	62.0		
1500° F. oil/1300° F.*	99,450	71,240	22.0	51.4		
1500° F. oil/1300° F.*	94,100	67,460	28.0	69.0		
As rolled, 4"X4" billet..	93,000	72,000	26.0	50.0		
1460° F. water/1000*..	168,420	153,720	19.0	52.6	311	44
1460° F. water/1100*..	143,060	128,860	19.0	60.2	277	36
1460° F. water/1200*..	112,930	120,750	22.0	60.5	262	35
1460° F. water/1300*..	120,550	109,540	25.0	67.6	212	30
8" round as hammered ..	95,000	50,000	22.0	50.0		

\* Tests from 1-in. rounds.

Critical range diagrams are shown in Figs. 175 and 176.

Results obtained upon oil quenching from 1400° F. and subsequent toughening of 1-in. rounds of the approximate composition of 0.70 per cent. carbon, 0.60 manganese and 0.50 chrome are given in the following table; note especially the high proportion

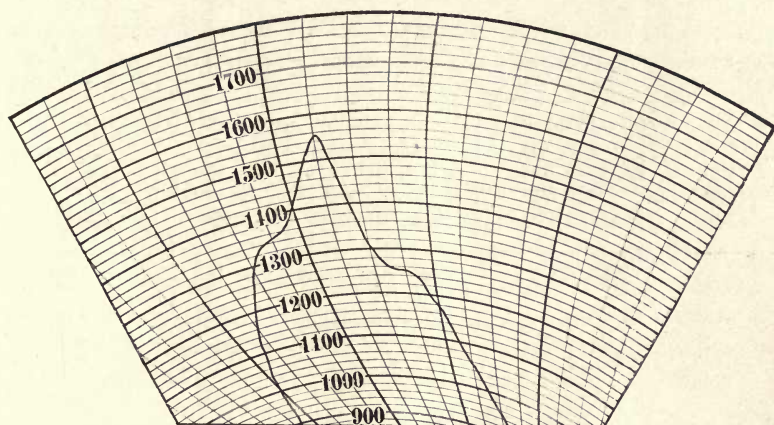


FIG. 175.—Critical Range Diagram of Heat 2101. Carbon, 0.47 per cent.; Manganese, 0.60 per cent.; Phosphorus, 0.006 per cent.; Sulphur, 0.025 per cent.; Silicon, 0.108 per cent.; Chrome, 0.51 per cent.

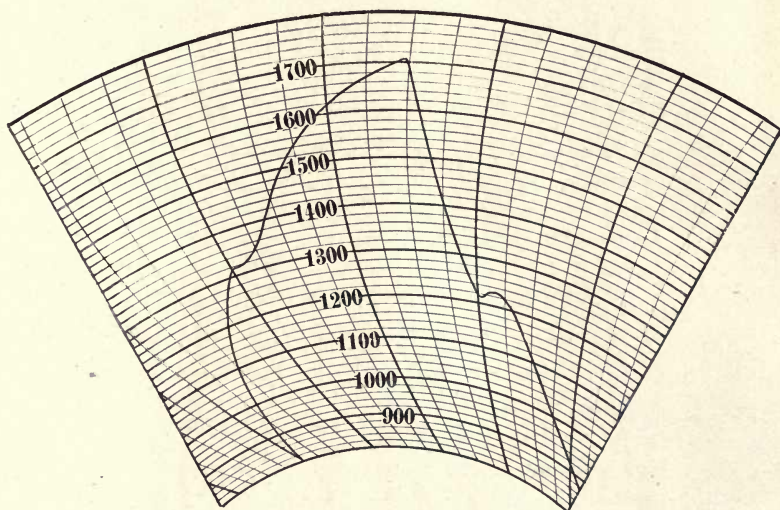


FIG. 176.—Critical Ranges of Basic Open-hearth Steel, Heat 8148. Carbon, 0.50 per cent.; Manganese, 0.49 per cent.; Phosphorus, 0.010 per cent.; Sulphur, 0.026 per cent.; Silicon, 0.05 per cent.; Chrome, 0.57 per cent.

of the elastic limit to the tensile strength, combined with good ductility:

Toughening Temperature, °F.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation, Per Cent. in 2 Ins.	Reduction of Area, Per Cent.
900	199,500	179,050	6.0	25.6
1000	168,900	143,500	12.5	33.8
1100	145,700	119,400	15.0	42.2
1200	120,000	105,000	17.0	47.5
1300	107,100	91,400	22.0	58.1

The critical range diagram is shown in Fig. 177

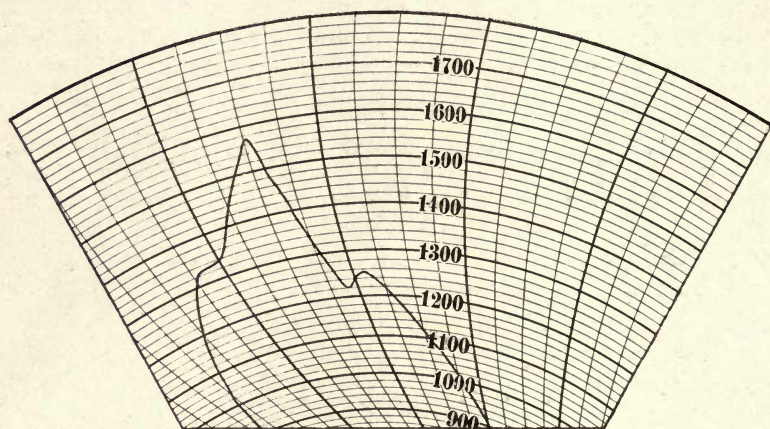


FIG. 177.—Critical Range Diagram of Chrome Carbon Steel. Carbon, Approx. 0.70 per cent.; Manganese, Approx. 0.60 per cent.; Chrome, Approx. 0.50 per cent.

#### 1.00 PER CENT. CHROME STEELS

Chrome steels with about 1.00 per cent. chrome, with high carbon, find their greatest use in balls, ball-races, cones, roller bearings, crushing machinery, safe steel, tools, and other parts requiring a very hard surface. The use of about 1 per cent. each of carbon and chrome appears to give the highest combination of "tough-hardness" and plasticity. Such steel requires care in forging, which must be done at a good red heat and with powerful blows. As forged, the steel is much too hard for ordinary machine work and must therefore be thoroughly annealed.

**Annealing.**—Annealing at the usual annealing temperatures for an ordinary length of time will not generally suffice, due to the slow-



ness with which the cementite is taken into solid solution by the austenite, and which is well illustrated by the following case: A number of 3-in. forged rounds were annealed at 1400° F. for four hours and slow cooled with the furnace, but were then too hard for machining; they were reannealed for sixteen hours in a similar manner, and although the grain was refined, they could be sawed only with difficulty. The most expeditious method for annealing this steel is to normalize and then anneal, as follows: first thoroughly heat the steel at a temperature above the Ac<sub>m</sub> point for the "solution" of the cementite, air cool to a temperature beneath that of the Ar point to prevent disintegration, reheat to a temperature slightly over the Ac<sub>1.2.3</sub> point to refine the grain, and slow cool in the furnace or in lime to obtain the maximum degree of ductility (softness). After such a treatment the steel is easily machinable and will have a Brinell hardness of about 130 to 170. For a steel containing 1.00 to 1.40 per cent. carbon, under 0.50 per cent. manganese, and about 1.00 per cent. chrome, the following temperatures may be used to advantage:

1. Heat to 1700° to 1750° F.
2. Air cool to about 800° F.
3. Heat to 1400° F.
4. Slow cool in furnace or in lime.

Note.—Add 35° to the temperatures (1) and (3) if the chrome is up to 1.50 per cent.

If, however, it is desired to anneal the steel by the straight anneal only (i.e., using but one temperature and one heating), this may be done by a prolonged length of heating, followed by a very gradual and extremely slow cooling. Thus the 3-in rounds previously referred to were satisfactorily annealed by heating to a temperature of about 1400° F., maintaining this temperature for about sixty hours, and then cooling with extreme slowness through the critical range. This is the more common method used by manufacturers of chrome steel for roller bearings (about 1 per cent. carbon and 1.25 to 1.50 per cent. chrome); the temperatures vary between 1400° and 1475° F.; the length of time varies upon the mass of the charge, and usually takes several days. Such steel in the full annealed condition should have a Brinell hardness of not over 170.

**Hardening.**—These steels take on great hardness, both on the surface and at depth, when hardened, for which either water or oil may be used. In the hardened condition the Shore scleroscope

gives a hardness figure of about 100. The critical ranges for these steels with over 0.90 per cent. carbon will vary from 1330° to 1375° F. for 0.5 per cent. chrome, to 1400° to 1450° for 1.5 per cent. chrome. The results obtained from the heat treatment of 1-in. rounds of a 0.64 per cent. carbon chrome steel are as follows:

0.64 CARBON; 0.28 MANGANESE; 0.17 SILICON; 1.04 CHROME.

Quenched in Oil from 1600° F. and Toughened at — Deg. F.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation, Per Cent. in 2 Ins.	Reduction of Area, Per Cent.	Brinell Hardness.
750	227,500	170,000	5.0	13.5	477
930	212,000	155,000	8.0	19.5	444
1110	186,000	127,500	10.0	22.5	387

#### 2.00 PER CENT. CHROME STEELS

The tables on page 303, taken from the work of McWilliams and Barnes,<sup>1</sup> and rearranged, show the physical properties of 2 per cent. chrome steels of ascending carbons as rolled, heat treated and annealed. Chrome steels with about 2 per cent. of chrome are largely used in the manufacture of armor-piercing projectiles, besides in such objects which require an extremely hard-wearing surface such as in crushers, cold rolls, drawing dies, special files, etc.

#### HIGH-CHROME CARBON STEELS

For general practical purposes and heat-treatment work the chrome content is limited to that percentage below which the steel as cast will be pearlitic—that is, the critical temperatures on cooling are all above atmospheric temperatures and the steel structure is composed of pearlite plus either ferrite or cementite. The hardness increases with the chrome content, and, according to Arnold and Read, appears to be independent of the carbon content, whilst the brittleness is far less than in carbon steels of the same carbon content.

**Martensitic Steels.**—When the chrome content reaches from 5 to 7 per cent., dependent upon the carbon, the change point, *A<sub>r</sub>*, will fall below normal temperatures and the structure will become troostitic or martensitic. That is, the structure will be comparable with that of a straight carbon steel in the hardened condition. These

<sup>1</sup> "Iron and Steel Inst. Journ."

## 2.00 CHROME—0.20 CARBON.

CRITICAL RANGE  $A_{c3}=1512^{\circ}\text{F.}$ 

Treatment.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation, Per Cent. in 2 Ins.	Reduction of Area, Per Cent.	Alternations (Arnold's).
1. As rolled.....	70,400	45,600	30.5	71.2	331
2. 1475° F. in water/ 750° F.	137,200	134,000	12.5	40.6	96
3. 1475° F. in water/1025° F.	116,000	110,000	16.0	50.7	144
4. 1475° F. in water/1300° F.	82,400	64,000	28.0	70.2	234
5. Annealed.....	66,000	32,000	40.5	77.9	410

## 2.00 CHROME—0.25 CARBON.

CRITICAL RANGE  $A_{c3}=1490^{\circ}\text{F.}$ 

1. As rolled.....	67,200	48,800	30.0	68.4	312
2. 1475° F. in water/ 750° F.	176,400	156,600	12.0	42.5	103
3. 1475° F. in water/1025° F.	144,000	136,000	14.5	51.5	99
4. 1475° F. in water/1300° F.	96,000	82,000	25.0	68.6	204
5. Annealed.....	70,000	32,000	39.5	73.8	437

## 2.00 CHROME—0.32 CARBON.

CRITICAL RANGE  $A_{c3}=1445^{\circ}\text{F.}$ 

1. As rolled.....	92,600	60,000	26.0	65.4	355
2. 1475° F. in water/ 750° F.	200,000	184,000	9.5	37.0	94
3. 1475° F. in water/1025° F.	159,200	151,800	15.0	52.2	141
4. 1475° F. in water/1300° F.	109,600	94,000	22.5	67.2	197
5. Annealed.....	60,800	28,800	37.0	70.7	482

## 2.00 CHROME—0.50 CARBON.

CRITICAL RANGE  $A_{c3}=1432^{\circ}\text{F.}$ 

1. As rolled.....	107,600	64,000	20.5	65.8	378
2. 1475° F. in water/ 750° F.	228,200	224,000	9.0	30.3	88
3. 1475° F. in water/1025° F.	179,200	170,200	13.0	42.5	111
4. 1475° F. in water/1300° F.	124,800	114,000	21.0	61.5	169
5. Annealed.....	75,200	25,400	28.0	55.4	440

## 2.00 CHROME—0.65 CARBON.

CRITICAL RANGE  $A_{c3}=1440^{\circ}\text{F.}$ 

1. As rolled.....	142,600	116,000	14.5	41.1	292
2. 1475° F. in water/ 750° F.					
3. 1475° F. in water/1025° F.	193,000	188,200	10.0	32.4	74
4. 1475° F. in water/1300° F.	125,200	113,600	21.0	55.6	133
5. Annealed.....	97,800	64,000	21.5	62.2	214

## 2.00 CHROME—0.85 CARBON.

CRITICAL RANGE  $A_{c3}=1430^{\circ}\text{F.}$ 

1. As rolled.....	151,800	104,000	10.0	18.3	178
2. 1475° F. in water/ 750° F.					
3. 1475° F. in water/1025° F.	191,400	185,000	8.5	28.2	65
4. 1475° F. in water/1300° F.	126,000	115,000	20.0	51.7	155
5. Annealed.....	80,200	37,600	32.0	63.5	316



steels have high tensile strength and elastic limit, low ductility, great hardness and medium brittleness. Heat treatment has little or no influence, except, perhaps, to refine the grain. On account of their physical characteristics these steels are but little used, except as applied to special tool steel. As the chrome content is again increased to about 12 to 15 per cent., intensely white grains of the double carbide of chrome and iron form within the martensite, and

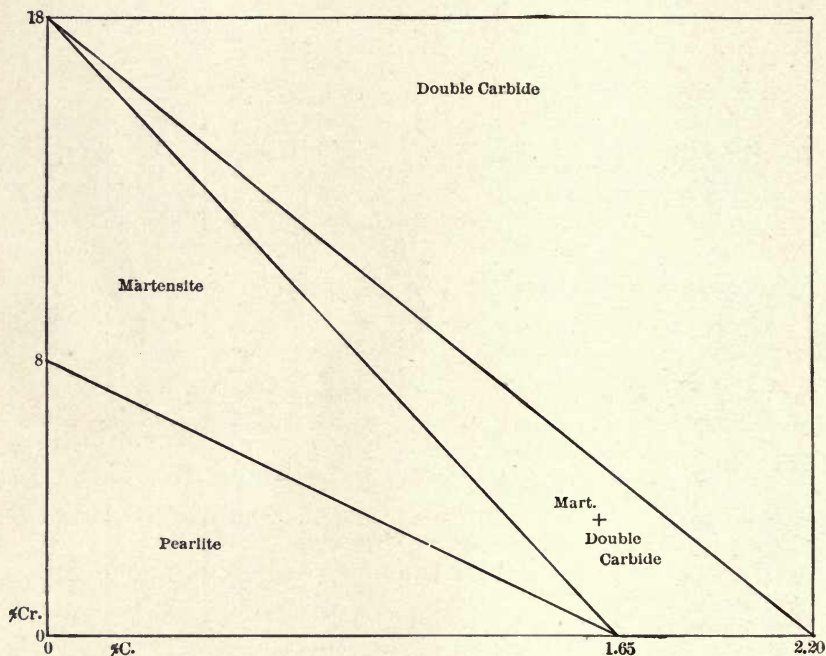


FIG. 178.—Microscopic Constituents of Chrome Carbon Steels.

gradually occupy the whole field with further increase of chrome. These structural changes for varying percentages of chrome, and with 0.2 and 0.8 per cent. carbon respectively, are given by Guillet as follows:

Structure	With 0.2 Carbon	With 0.8 Carbon
Pearlitic.....	0 to 7 per cent. Cr.	0 to 5 per cent. Cr.
Troostitic.....	7 to 8 per cent. Cr.	5 to 18 per cent. Cr.
Martensitic.....	8 to 13 per cent. Cr.	
Martensite plus double carbide	13 to 20 per cent. Cr.	18 and over per cent. Cr.
Double carbide.....	over 20 per cent. Cr.	

These changes are shown graphically in Fig. 178.

The effect of annealing and heat treatment upon high-chrome carbon steels, with approximately 0.4 per cent. carbon is given in the following table:<sup>1</sup>

HEAT TREATMENT OF HIGH-CHROME STEELS, 0.4 CARBON

Chrome, Per Cent	Treatment.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit Lbs. per Sq. In.	Elong- ation Per cent. in 2 Ins.	Reduction of Area, Per Cent.
5	Annealed . . . . .	53,760	39,872	24	24.0
	Hardened & tempered	123,648	109,312	12	37.0
10	Annealed . . . . .	94,080	51,296	21.5	44.0
	Hardened & tempered	121,632	94,976	12	53.6
15	Annealed . . . . .	101,472	56,896	18.5	50.0
	Hardened & tempered	130,144	109,312	11.5	54.6
20	Annealed . . . . .	80,864	47,488	21.5	46.5
	Hardened & tempered	90,272	61,824	19.5	51.5
25	Annealed . . . . .	94,526	66,752	18	62.1
	Hardened . . . . .	90,496	61,824	20	50.0
30	Annealed . . . . .	93,184	71,232	19	62.0
	Hardened . . . . .	87,360	64,518	19	65.0

Further data on high-chrome steels may be obtained from the researches of Guillet,<sup>2</sup> Portevin,<sup>3</sup> Arnold and Read,<sup>4</sup> Becker,<sup>5</sup> Mars,<sup>6</sup> and others.

<sup>1</sup> J. Holtzer & Cie., Loire, France, from Harbord's "Metallurgy," I, 391.

<sup>2</sup> Guillet, "Les Aciers Speciaux."

<sup>3</sup> A. Portevin, "Revue de Metallurgie," 1909, No. 12, p. 1264, "Metallurgie," 1910, Heft 6, s. 177.

<sup>4</sup> Arnold and Read, "Iron and Steel Inst. Journ."

<sup>5</sup> O. M. Becker, "High-speed Steel."

<sup>6</sup> Mars, "Spezialstähle." 1912.

## CHAPTER XIII

### CHROME NICKEL STEELS

**Chrome Nickel vs. Chrome Vanadium Steels.**—Chrome nickel steels, as a type composition, probably represent the best all-around alloy steels in commercial use for general purposes. By this it is not to be inferred that chrome nickel should always be used in preference to other alloys; as a matter of fact, each type is more or less peculiarly adapted to work of a distinctive nature. On the other hand, chrome nickel steel of suitable composition will satisfy nearly every condition for structural and similar purposes. Much has been said and done with chrome vanadium steels, and while the latter undoubtedly do fill a long-felt want along certain lines, it should not be said that chrome vanadium steels are superior to chrome nickel steels. In fact, with a few exceptions, chrome nickel steels of suitable composition will generally measure up to any standards set by the ordinary vanadium alloys and at equal or at even less cost. Neither chrome vanadium, nor chrome nickel, nor any one type of steel is a general prescription for the every ill of the steel user: each steel has its distinctive characteristics and applications. And notwithstanding the mass of advertising "literature" to the contrary, it would also be decidedly improper to state, as a general rule, that either is superior to the other.

**Influence of Chrome and Nickel.**—Chrome nickel steels of suitable composition appear to have the beneficial effects of both the chrome and nickel, but without the disadvantages which are inherent in the use of either one separately. Moreover, the presence of both chrome and nickel seems to intensify certain physical characteristics. To the increased ductility and toughness conferred by nickel on the ferrite there is added the mineral hardness given to the cementite and pearlite by the chrome, but with a greater resultant effect. Again, while the addition of nickel alone serves to diminish the susceptibility to brittleness in the steel upon prolonged heating or sudden cooling—in comparison with the corresponding straight carbon steels—and, on the other hand, the presence of chrome



alone tends to the opposite effect, a suitable combination of the two alloying elements tends to neutralize the harmful effects and also to magnify the good points. This is not only brought out in the static strength and ductility, but also in the dynamic strength or fatigue resistance.

Statements have frequently appeared in print to the effect that nickel "poisons" the steel dynamically; that chrome has little influence one way or the other upon the fatigue resistance; and that chrome nickel steels are inferior along these lines to certain other specific alloy steels. In considering these broad statements there are three things in particular which should be noted. Firstly, that in the present state of the art of dynamic strength testing, the results so obtained are often widely divergent for the same steel, not to mention any comparison of results upon different steels of dissimilar type. Secondly, even assuming that concordant and strictly comparative results could be thus obtained by means of the testing machines now in use, the majority of the experimental results put forth to prove the general inferiority (dynamically) of chrome nickel steels in relation to certain other types (e.g., chrome vanadium) are oftentimes not really comparative at all, since the two distinctive types of steel have been heat treated alike. That is, while it may be perfectly good practice to quench a chrome vanadium steel from say 1650° F., it might be distinctively poor practice to quench a chrome nickel steel from the same temperature. And yet many "comparative" results have been obtained in just such a manner, to the detriment of either one steel or the other. Rather, then, should each steel be treated in that impersonal and strictly scientific manner which will tend to bring out the maximum qualities of each; and then should the tests be made upon the same machine under like conditions. Thirdly, whatever may be the influence of chrome or nickel alone upon the dynamic strength of steel, it has been repeatedly demonstrated that the proper combination of the two alloys undoubtedly produces a type of metal with vastly improved capacity for resistance to fatigue.

**Commercial Ratio of Chrome and Nickel Content.**—From the author's experience in both the manufacture and use of chrome nickel steels it would appear that there is some ratio existing between the proportion of the chrome and nickel which will give the most efficient combination of physical characteristics. In other words, by combining the chrome and nickel in some such ratio, the less susceptibility to brittleness upon prolonged heating which is char-

acteristic of nickel additions will modify the greater susceptibility to brittleness which is given by chrome alone, giving a stronger and better steel than may be obtained when this ratio is not observed. Again, it will be observed that if the chrome content greatly exceeds a certain proportion in respect to the nickel, the steel will be more difficult to heat treat successfully, the temperature limits are more narrow, and the possibility of poor results is greatly increased. This best ratio is probably about  $2\frac{1}{2}$  parts of nickel to about 1 part of chrome. Thus we have the principal standard types of 3.5 nickel

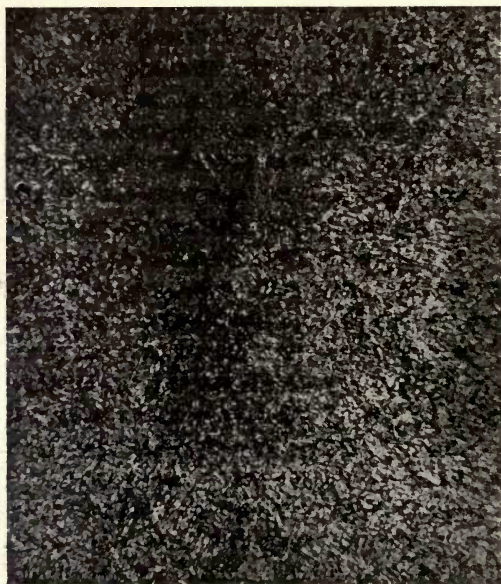


FIG. 179.—Protective Deck Steel. (Bullens.)

and 1.5 chrome, 1.5 nickel and 0.6 chrome, and various intermediate types.

**Carburization.**—The carburization of chrome nickel steels does not differ in principle from that previously described. These steels generally carburize more rapidly and better than straight carbon steels, and, in particular, give the characteristic gradual cemented zone which should always be aimed for. The presence of suitable proportions of chrome and nickel, as previously mentioned, also gives that low brittleness of core which is so desirable; this fact even permits the use of steels up to some 0.3 per cent. carbon without

great danger. The use of chrome nickel steel in case-hardening work covers a wide range—from small gears subject to great shock and wear to the heaviest grades of armor plate.

**Heat Treatment.**—The heat treatment of these steels does not present any new problems. In the main the discussion under the chapters on Carbon Steels and Nickel Steels will apply equally well to chrome nickel steels. Similarly to nickel steels, these steels are less susceptible to the deleterious influence of high temperatures, and which will be subsequently mentioned. Suitable heat treatment will develop a very fine micro-structure, as is shown in Fig. 179, representing the structure of specially treated chrome nickel steel used for protective deck plate on battleships; the physical properties on this particular steel were:

Tensile strength, lbs. per sq. in.....	132,000
Elastic limit, lbs. per sq. in.....	116,700
Elongation, per cent. in 2 ins.....	23
Reduction of area, per cent.....	64

Proper annealing will likewise develop a good micro-structure in the steel, as is shown in Fig. 40. The critical ranges of chrome nickel steels are somewhat lower than those of the corresponding straight carbon steels, so that lower temperatures may be used for quenching.

In general, the best treatments which can be given to these alloy steels after forging are as follows:

## I

- a. Quench in oil from about 175° to 200° F. over the critical range.
- b. Quench in oil from about 50° over the critical range.
- c. Anneal at about 75° under the critical range (also see II). Machine.
- d. Quench in the proper medium from about 50° over the range.
- e. Draw the temper to suit the work in hand.

## II

For shafts and other structural parts in which the desired physical properties may be obtained by a drawing temperature of about 900°



F. or over, and which will leave the steel in a machinable condition, Treatment I may be modified at (c) as thus noted, and no further treatment will be required. But if the drawing temperature must be much lower, as for gears, the full treatment as in (I) is advisable.

- a. Quench in oil from about 175° to 200° F. over the critical range.
- b. Quench in oil from about 50° over the critical range.
- c. Draw at 900° or more, as the work may require. Machine.

### III

The full treatment as given under (I) may be modified, if desired, to the following, for parts to be drawn below 900° or 1000° F.:

- a. Quench in oil from about 175° to 200° over the critical range.
- b. Reheat to about 25° to 50° F. over the critical range and cool slowly. Machine.
- c. Quench in oil from about 50° over the critical range.
- d. Draw to the temperature required by the work.

### LOW CHROME NICKEL STEELS

The low chrome nickel steels, containing approximately 0.5 per cent. chrome and 1.5 per cent. nickel, are the most used of all the chrome nickel alloys. After forging or rolling, this grade of synthetic steel may be heat treated to develop physical characteristics nearly equivalent to a 3.5 per cent. nickel steel of similar carbon content. It does not have the objectionable tendency to laminate which may characterize the latter steel, and on account of the less cost of alloys, this chrome nickel steel is sold at a price considerably lower than that of 3.5 per cent. nickel steel. This grade of chrome nickel steel forges well and machines easily, does not require the more narrow temperature limits in heat treatment as do some steels containing a larger, although not as well proportioned, amount of chrome and nickel.

The physical tests obtained from heat-treated steel of 1-in. sections, containing approximately 0.5 per cent. chrome and 1.5 per cent. nickel, are given in the charts in Figs. 180 to 183.

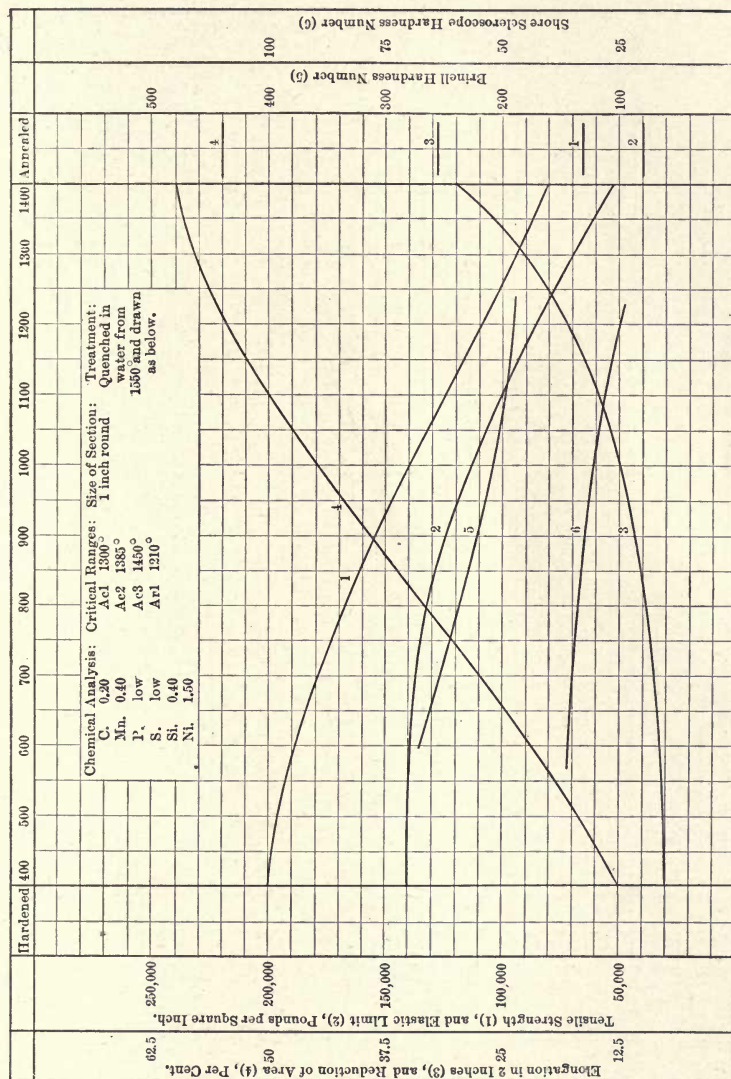


FIG. 180.—Normal Characteristics of 0.20 Carbon Low Chrome Nickel Steel, Heat Treated.

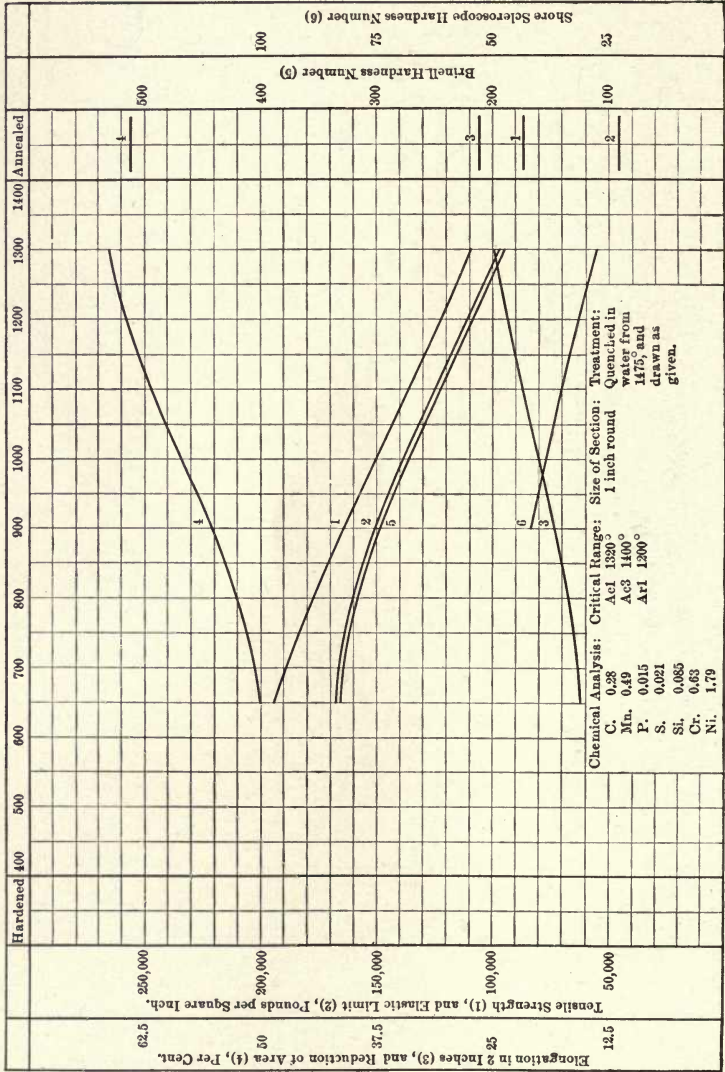


Fig. 181.—Normal Characteristics of 0.30 Carbon, Low Chrome Nickel Steel, Heat Treated.





Fig. 182.—Normal Characteristics of 0.40 Carbon, Low Chrome Nickel Steel, Heat Treated.

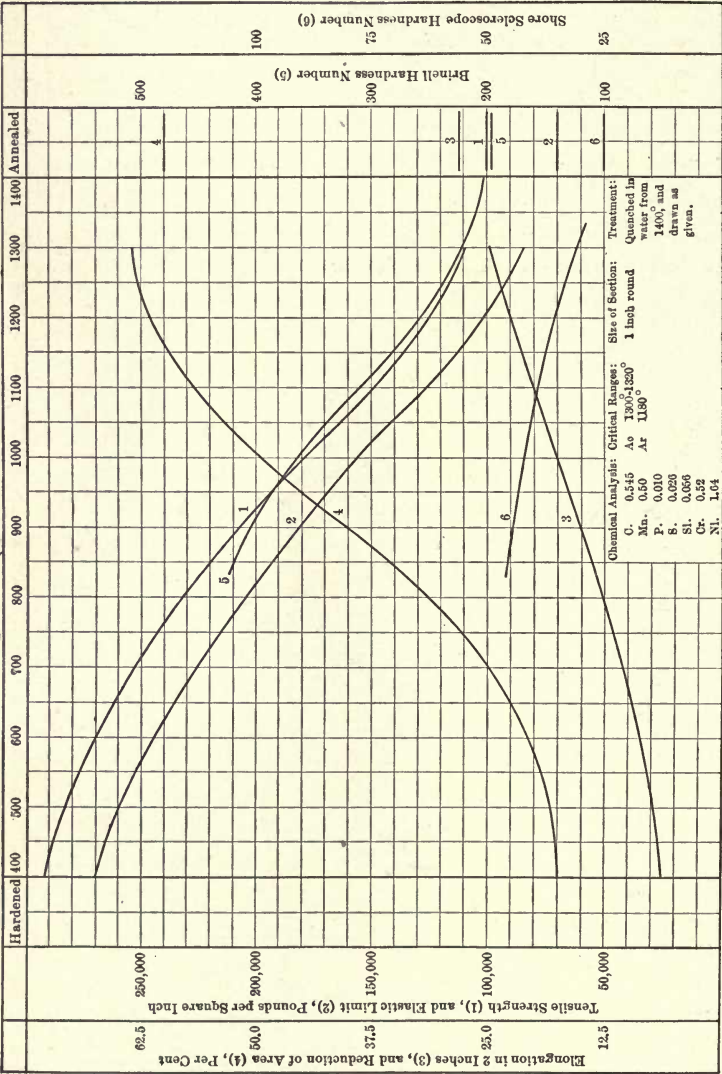


Fig. 183.—Normal Characteristics of 0.55 Carbon, Low Chrome Nickel Steel, Heat Treated.

Small automobile forgings specifying 0.20 to 0.27 per cent. carbon (with the above amount of chrome and nickel) may readily be heat treated to fulfill the requirements of:

Tensile strength, lbs. per sq. in. ....	100,000
Elastic limit, lbs. per sq. in. ....	85,000
Elongation, per cent. in 2 ins. ....	16

The critical range of steels of this analysis is about 1425–1450° F.; a quenching temperature of 1475° to 1500° will generally give the best results in small sections which only require a single quenching.

An interesting comparison between this grade of chrome nickel steel and 3½ per cent. nickel steel with the same carbon content is shown by the following requirements for automobile axles of a diameter of 1½ ins. as specified by one manufacturer:

SPECIFICATION FOR HEAT-TREATED AUTOMOBILE AXLES, 1½-in. DIAM.

	Chrome Nickel Steel.	Nickel Steel.
Carbon.....	0.30 to 0.40	0.30 to 0.40
Manganese.....	0.50 to 0.70	0.50 to 0.70
Phos. and sul.....	under 0.04	under 0.04
Silicon.....	0.20	0.20
Nickel.....	1.50	3.50
Chrome.....	0.50	
Tensile strength, lbs. per sq. in.....	120,000	135,000
Elastic limit, lbs. per sq. in.....	110,000	120,000
Elongation, per cent. in 2 ins.....	16	16.5
Reduction of Area, per cent.....	45	50
Bend test, flat around.....	180°	180°

The following results were obtained from test pieces taken from full-size forgings of approximately 8 to 10 ins. in diameter, and having an analysis of carbon 0.38 per cent., manganese 0.55 per cent., chrome 0.31 per cent., and nickel 1.20 per cent. Many interesting points were noticed in the treatment of this grade of steel approximating the analysis given, and especially the seeming contradiction of the annealing and hardening temperatures. The critical range of this steel is approximately 1340° to 1360° F. Forgings annealed at temperatures slightly above these show perfect annealing. If the annealing temperature should be raised, it is at the expense of ductility, and the fracture becomes coarsely crystalline



and shows "fire." The physical properties thus obtained are shown in the following table:

Treatment.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation Per Cent. in 2 Ins.	Reduction of Area, Per Cent.
As forged.....	86,500	45,000	21	34.6
Annealed at 1360°-1380°	75,250	35,500	33	57.9
	74,300	35,000	30	50.1
Annealed at 1550°-1575°	77,750	42,000	17	26.0

Unless previously normalized (as by air cooling from a temperature such as used in the high-temperature anneal above), or double quenched as outlined in the treatments previously given, the hardening of sections of say 3 ins. diameter or more demands the use of a temperature some 200° over the critical range to bring out the full effects of this combination of chrome and nickel. This is true of both oil and water quenching, but more noticeably so in the case of oil baths. Parenthetically, it is interesting to compare such treatment with that which has been previously described under nickel steels; the technical reasons will then be clear. It is the author's experience, as well as that of numerous others, that a hardening temperature of 1550° to 1580° F. is required if the steel has not been previously treated; take for example the following tests on an 8-in round bar:

Quenched in Oil from Deg. F.	Drawn at Deg. F.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation, Per Cent. in 2 Ins.	Reduction of Area, Per Cent.
1450	900	79,750	46,750	28.0	58.9
1500	900	88,300	53,000	23.5	55.4
1580	1050	99,000	71,500	23.5	61.9
1580	1050	92,200	63,600	27.0	62.4
1580	1050	95,880	70,700	24.0	62.0

It will be noticed that the quenching heat of 1580° F. not only gives higher tensile strength, elastic limit and ductility, but also permits of a drawing temperature some 150° higher. Microscopically the structure obtained by the high-quenching temperature is excellent, as is shown in Fig. 184. The structure of the same piece after forging, and before treatment, is shown in Fig. 185.

Steel with approximately 0.50 per cent. chrome, 1.50 per cent. nickel and about 0.40 carbon may be readily heat treated to fulfill

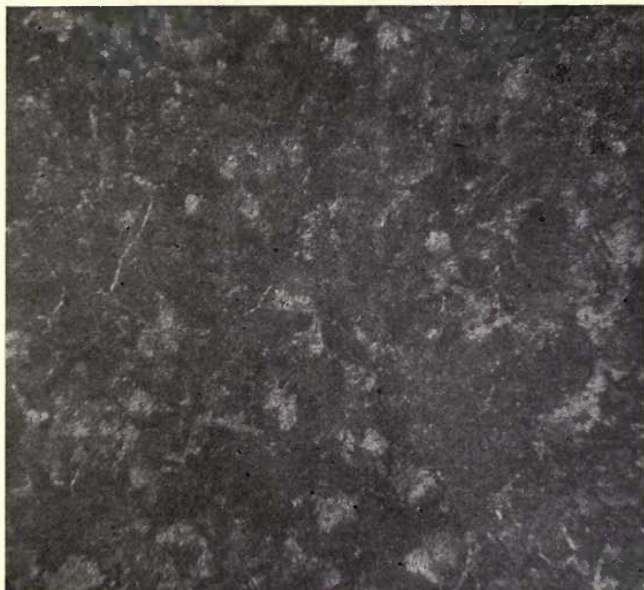


FIG. 184.—Chrome Nickel Steel Axled, Oil Quenched from 1580° F., Drawn at 1050° F.  $\times 100$ . (Bullens.)



FIG. 185.—Chrome Nickel Steel Axle as Forged.  $\times 100$ . (Bullens.)

the specification, in large sections up to 12 ins. diameter, and with proportionally higher tensile results in small sections, of:

Tensile strength, lbs. per sq. in. ....	90,000
Elastic limit, lbs. per sq. in. ....	60,000
Elongation, per cent. in 2 ins. ....	22
Reduction of area, per cent. ....	50

The following equations connecting maximum strength, Brinell hardness number and scleroscope hardness number have been computed<sup>1</sup> from several hundred tests made with low chrome nickel steel (1.5 per cent. nickel and 0.5 per cent. chrome) of different carbon content and heat treated to bring out all possible physical properties:

$$(1) \quad M = 0.68 B - 22.$$

$$(2) \quad M = 3.7 S - 1.$$

$$(3) \quad B = 5.4 S + 33.$$

$M$  = maximum strength in units of 1000 lbs. per sq. in.

$B$  = the Brinell hardness number.

$S$  = the scleroscope hardness number.

The maximum strength corresponding to different Brinell values as determined by equation (1) for these steels is as follows:

Brinell.	Maximum Strength, Lbs. per Sq. In.	Brinell.	Maximum Strength, Lbs. per Sq. In.
100	46,000	350	216,000
150	80,000	400	250,000
200	114,000	450	284,000
250	148,000	500	318,000
300	182,000	550	352,000

The maximum strength corresponding to different scleroscope values as determined by equation (2), and the corresponding Brinell numbers as determined by equation (3), for these steels, are as follows:

<sup>1</sup>R. R. Abbott, A. S. T. M., Vol. XV, Part II, 1915, p. 43 et seq.



Scleroscope.	Maximum Strength, Lbs. per Sq. In.	Brinell.
20	73,000	141
30	110,000	195
40	147,000	249
50	184,000	303
60	221,000	357
70	258,000	411
80	295,000	465
90	332,000	519
100	369,000	573

## HIGH CHROME NICKEL STEELS

Chrome nickel steels containing approximately 3.5 per cent. nickel and 1.5 per cent. chrome comprise a type of steel with distinctive physical characteristics, but which obviously are not shown by the results of ordinary pull test values when taken in comparison with the low chrome nickel steels. The following figures, giving the ordinary physical properties, illustrate the latter point. Dependent upon the section, treatment, and carbon content (0.2 to 0.5 per cent.), they may be given as follows:

Composition.	Tensile Strength.	Elastic Limit.	Elongation.	Reduction of Area.
3.5 Nickel 1.5 Chrome	85,000 to 275,000	55,000 to 265,000	26 to 10	65 to 35
1.5 Nickel 0.5 Chrome	80,000 to 264,000	56,000 to 240,000	30 to 8	70 to 27.5

It is evident, since the above results show but little difference, that the superiority of the high chrome nickel steel does not appear in the static properties. On the other hand, there is a tremendous difference between the two types (in favor of the higher alloy) in the dynamic and endurance strength, such as freedom from brittleness and resistance to shock. This is illustrated by certain specific uses, as examples, to which these steels are put and which demand the highest attainable combination of dynamic strength, resistance to shock, and high static strength. Thus with about 0.2 to 0.3 per cent. carbon these steels are used in protective deck plate, requiring that peculiar combination of properties which comprise ballistic strength; with a slightly higher carbon content, and certain other modifications, we have a typical Krupp armor plate; and

with 0.45 to 0.50 per cent. carbon these steels are used in high-duty gears, and in which it is possible to hammer one tooth against its neighbor without breaking it off.

Or, as it has been expressed in every-day terms, the effect of the larger amounts of alloys in suitable combination is like a comparison between a trained athlete and the amateur. Each man may be able to lift a maximum weight of say 200 lbs. But when it comes to repeating that same feat a number of times in succession, the trained man, with his developed powers of endurance, will win every time. And thus it is with the high alloy steel.

Typical results for a steel of this type are given in the chart in Fig. 186.

The following equations connecting maximum strength, Brinell hardness number and scleroscope hardness number have been computed<sup>1</sup> from several hundred tests made with high chrome-nickel steel (3.5 per cent. nickel and 1 per cent. chrome) of different carbon content and heat treated to bring out all possible physical properties:

$$(1) \quad M = 0.71 B - 33.$$

$$(2) \quad M = 3.7 S - 3$$

$$(3) \quad B = 4.8 S + 58.$$

$M$  = maximum strength in units of 1000 lbs. per sq. in.

$B$  = the Brinell hardness number.

$S$  = the scleroscope hardness number.

The maximum strength corresponding to different Brinell values as determined by equation (1) for these steels is as follows:

Brinell .	Maximum Strength, Lbs. per Sq. In.	Brinell.	Maximum Strength, Lbs. per Sq. In.
100	38,000	350	215,000
150	73,000	400	251,000
200	109,000	450	286,000
250	144,000	500	322,000
300	180,000	550	357,000

The maximum strength corresponding to different scleroscope values as determined by equation (2), and the corresponding Brin-

<sup>1</sup> R. R. Abbott, A. S. T. M., Vol. XV, Part II, 1915, p. 43 et seq.

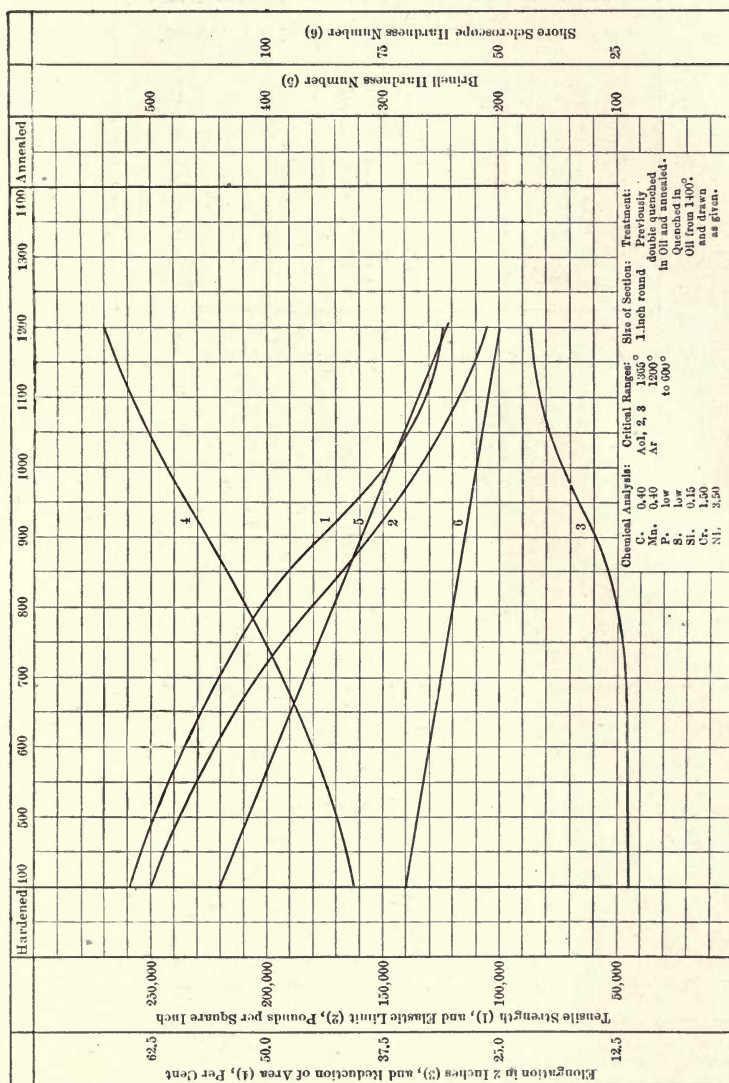


FIG. 186.—Normal Characteristics of 0.40 Carbon, High Chrome Nickel Steel, Heat Treated.



ell numbers as determined by equation (3), for these steels, are as follows:

Scleroscope.	Maximum Strength, Lbs. per Sq. In.	Brinell.
20	71,000	154
30	108,000	202
40	145,000	250
50	182,000	298
60	219,000	346
70	256,000	394
80	293,000	442
90	330,000	490
100	367,000	538

#### INTERMEDIATE TYPES OF CHROME NICKEL STEELS

Between the high and low composition types of chrome nickel steels previously given there are a great variety of combinations of the two alloying elements. Thus, in the chart in Fig. 187, we have the results obtained from the heat treatment of 1-in. rounds with 1.0 per cent. chrome and 1.75 per cent. nickel. Other results, from similar compositions, taken from representative practice in the automobile world are given as follows:

#### CARBON 0.26 TO 0.35.

Treatment.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation, Per Cent. in 2 Ins.	Reduction of Area, Per Cent.	Brinell Hardness.
Hardened. . . .	197,000	135,000	9	37	460 to 480
Toughened. . .	110,000	90,000	25	55	235 to 250
Untreated. . . .	106,000	70,000	18	45	

#### CARBON 0.46 TO 0.55.

Treatment. . . .	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation, Per Cent.	Reduction of Area, Per Cent.	Brinell Hardness.
Tempered. . . .	305,000	265,000	5	16	480 to 525
Toughened. . .	130,000	114,000	20	60	300 to 335
Annealed. . . .	95,000	68,000	26	30	180 to 200

The effect of mass upon the latter type of chrome nickel steel is shown in Fig. 188.

The chart in Fig. 189 gives the results of tests upon steel containing 0.75 per cent. chrome and 3.0 per cent. nickel, while Fig. 190 illustrates a characteristic French steel containing 0.50 per cent. chrome and 2.50 per cent. nickel.

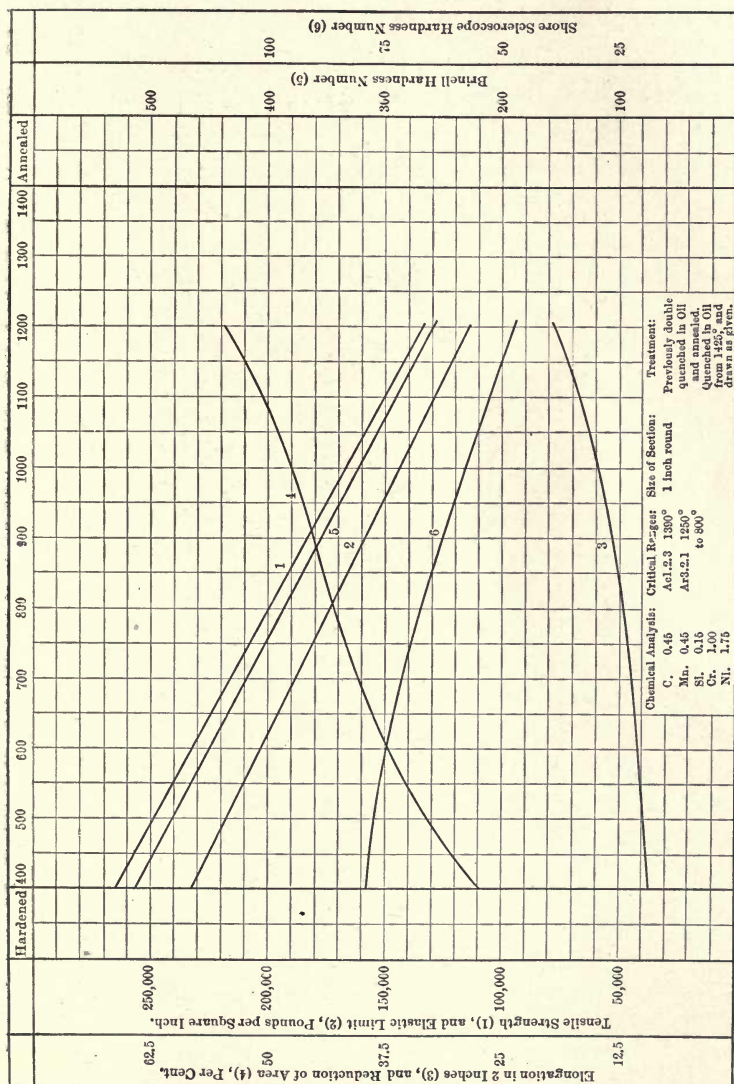


Fig. 187.—Normal Characteristics of 0.45 Carbon, Medium Chrome Nickel Steel, Heat Treated.

Steels with 0.60 per cent. chrome, 3.5 per cent. nickel, and 0.2 to 0.4 per cent. carbon, in medium-size forgings, may readily be treated to give a minimum of:

Tensile strength, lbs. per sq. in.....	120,000
Elastic limit, lbs. per sq. in.....	105,000
Elongation, per cent. in 2 ins.....	20

Illustrative of the relation of drawing temperatures to the carbon

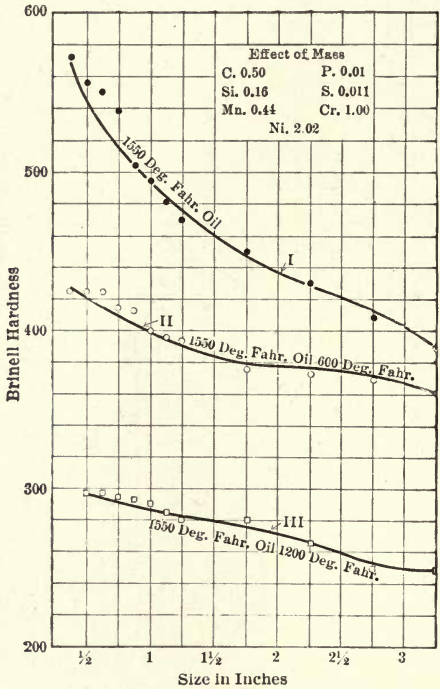


FIG. 188.—Effect of Mass upon the Hardness. (Matthews & Stagg.)

content for steels of this composition and with the same size of section,<sup>1</sup> to meet the above specification, the following may be of interest:

Per Cent. Carbon.	Drawing Temperature.
0.24	1150° F.
0.27	1200° F.
0.36	1240° F.

<sup>1</sup> Protective Deck Plate.



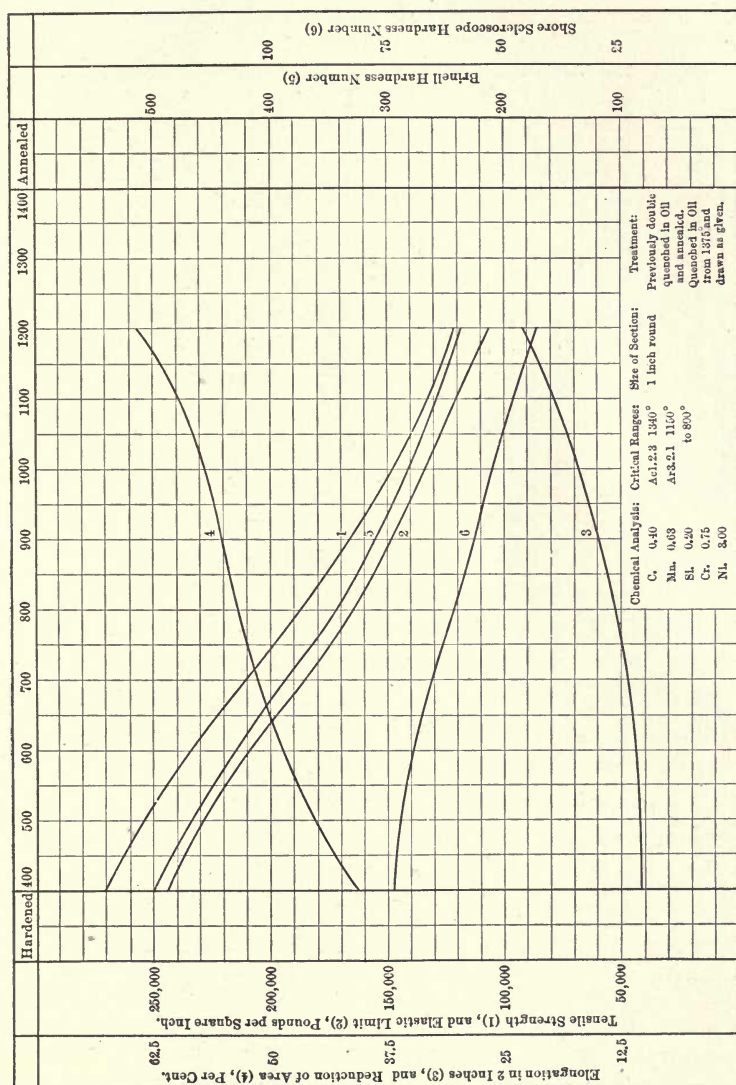


Fig. 189.—Normal Characteristics of 0.40 Carbon, Medium Chrome High Nickel Steel, Heat Treated.

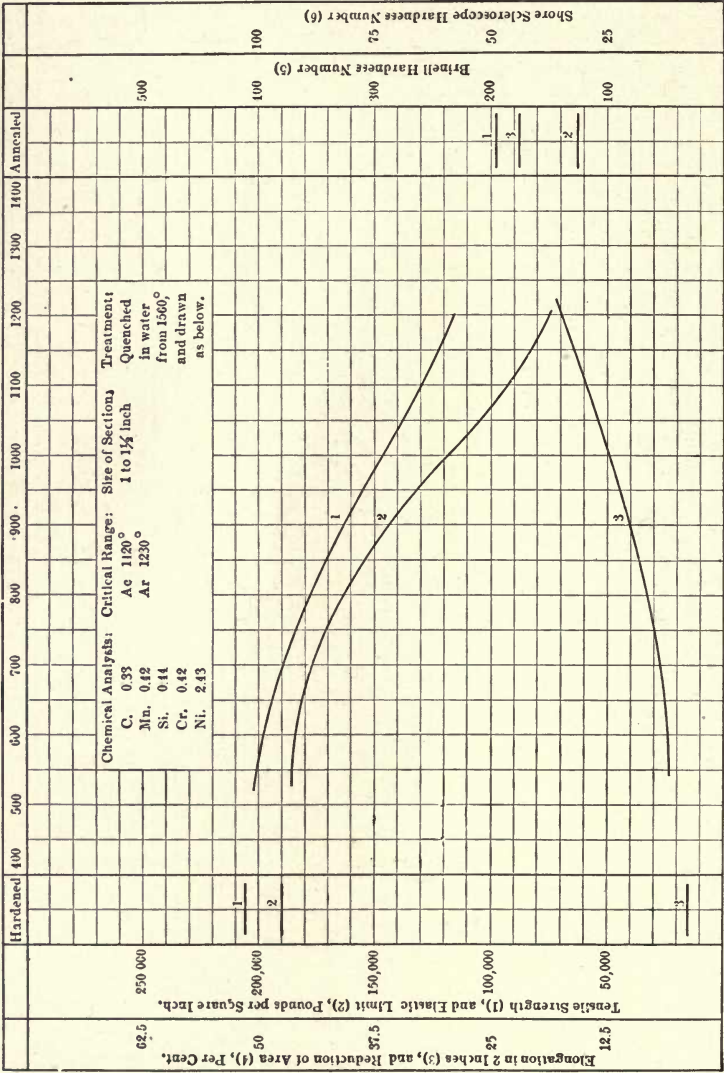


Fig. 190.—Normal Characteristics of 0.33 Carbon, 0.5 Chrome, 2.5 Nickel Steel, Heat Treated.

## SPECIAL CHROME NICKEL STEELS

The following tests by Revillon on various combinations of carbon, chrome and nickel in chrome nickel steels will be of interest:

## ANALYSES

No.	Carbon.	Man- ganese.	Phos- phorus.	Sulphur.	Silicon.	Chrome.	Nickel.
1	.22	.54	.009	.044	.36	.35	2.19
2	.25	.25	.027	.043	.08	.48	2.75
3	.425	.27	.006	.042	.20	1.20	2.86
4	.17	.53	.006	.053	.16	.18	3.47
5	.105	.43	.014	.030	.11	.85	4.38
6	.86	.23	.014	.030	.11	.86	.88
7	.25	.52	.006	.053	.17	1.28	3.82
8	.31	.70	.014	.021	.17	1.48	2.75
9	.42	.22	.013	.057	.11	.31	4.09
10	.45	.28	.014	.030	.11	.58	2.25
11	.52	.27	.006	.030	.39	.43	2.80
12	.77	.32	.014	.030	.11	.19	1.13
13	.10	.35	.003	.035	.31	1.75	5.36
14	.265	.24	.014	.030	1.27	2.33	4.40
15	.27	.39	.014	.030	.11	.85	4.90
16	.36	.37	.006	.053	.23	1.15	4.20
17	.39	.68	.018	.021	.35	.78	5.19

## CRITICAL POINTS

No.	Degrees Fahr.		No.	Degrees Fahr.	
	Ac.	Ar.		Ac.	Ar.
1	1472	1256	10	1418	1229
2	1463	1274	11	1472	1283
3	1508	1265	12	1508	1301
4	1454	1274	13	1400	860
5	1427	1139	14	1400	986
6	1418	1301	15	1490	986
7	1355	941	16	1418	770
8	1454	617	17	1436	482
9	1400	788			



## ANNEALED

No.	Annealing Temperature, Deg. F.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation, in 2 Ins. Per Cent.	Reduction of Area, Per Cent.	Guillery Shock Test.	Brinell Hardness Number.
1	1472	80,690	56,320	26	64.9	133.8	153
2	1472	87,690	61,160	23	55.7	65	170
3	1292	105,400	73,670	22	63.2	112.1	197
4	1652	87,760	50,200	21.5	53	36.1	168
5	1472	90,600	60,160	20	60.5	115.7	179
6	1382	137,960	72,960	11	23.8	21.7	210
7	1292	114,650	64,570	17.5	50.5		
8	1112	134,410	126,440	14.5	59.2	54.2	250
9	1112	115,930	99,560	18	65.8	101.2	217
10	1382	122,320	71,120	13	45.5	43.4	220
11	1382	135,830	81,780	14	49.8	54.2	251
12	1112	119,610	83,910	9.5	46.7	39.8	273
13	1112	163,850	142,940	13.5	58.4	137.4	178
14	1652	123,030	75,100	5.5	9.8	68.6	232
15	1382	142,510	93,870	6.5	28	39.8	288
16	1112	128,290	119,610	17	62.4	50.6	225
17	1112	147,210	91,600	14.5	52.8	47	268

NOTE: It will be noticed that in a number of instances the temperature used in the above annealing is under the Ac point, which will explain the high tensile results obtained. Such cases do not represent full annealing.

## HEAT TREATED

No.	Quenching Bath and Temperature, Deg. F.	Drawing Temperature, Deg. F.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation in 2 Ins. Per Cent.	Reduction of Area, Per Cent.	Guillery Shock Test.	Brinell Hardness Number.
1	Water, 1382	....	204,500	180,510	10	44.3	68.6	370
2	Oil, 1472	....	225,010	189,170	7	19.3	47	418
3	Oil, 1472	572	264,550	214,820	6.3	42.7	54.2	412
4	Oil, 1562	....	197,700	173,520	5	15.4	61.5	328
5	Water, 1382	....	201,970	173,520	10	54	72.3	295
6	Oil, 1382	932	230,410	221,880	1.5	4.3	36.1	388
7	Oil, 1562	....	208,370	183,350	9.5	51	47	343
8	Oil, 1472	....	292,280	289,440	9.5	36.3	57.8	425
9	Air, 1472	....	221,020	189,870	8	41	54.2	396
10	Water, 1472	932	190,580	173,520	6.5	47.8	79.5	301
11	Cil, 1472	572	215,530	202,250	7	42	43.4	395
12	Oil, 1472	932	210,500	181,930	6	14.1	32.5	425
13	Water, 1472	....	188,020	168,970	10	56	72.3	286
14	Water, 1562	....	183,190	160,010	10	52.5	57.8	298
15	Water, 1382	932	187,640	157,730	7	45.7	72.3	300
16	Air, 1562	....	235,390	225,860	9	24.5	54.2	402
17	Air, 1472	....	.....	.....	.....	.....	32.5	512

## CHROME NICKEL STEEL IN AUTOMOBILE CONSTRUCTION

*0.25 Carbon and under*

Principally for case-hardening purposes, such as bevel driving and transmission systems, steering-wheel pivot pins, cam rollers, push rods, and similar parts which must not only have a hard exterior surface, but possess strength as well.

*0.25 to 0.35 Carbon*

**Axles.**—Steering knuckles, bolts, pinions, steering pivots, spindles, driving shafts, etc., gears with light case, drawn. Gears hardened, but not drawn.

This grade of chrome nickel steel forges and machines well, and responds to heat treatment in matter of strength as well as of toughness.

*0.35 to 0.45 Carbon*

**Crankshafts.**—Countershafts, propeller shafts, live axles, diving shafts.

This grade possesses under suitable heat treatment a high degree of strength and considerable toughness. Its fatigue-resisting (endurance) properties are extremely high.

*0.45 to 0.55 Carbon*

**Tempered Gears.**—This grade probably gives the greatest possible hardness with the least possible brittleness (in combination) of any steel for transmission purposes.

## MAYARI CHROME NICKEL STEEL

Mayari steel is a "natural alloy" steel containing from .20 per cent. to .70 per cent. chrome and 1.00 per cent. to 1.50 per cent. nickel. It is made from a low-phosphorus Cuban ore containing the alloying elements chrome and nickel. In the blast furnace the chrome and nickel in the ore are reduced, forming a natural constituent of the iron. By means of the duplex process—Bessemer converter and open hearth—the iron is then made into steel, the chrome and nickel pass into the steel, forming a natural alloy, with no other addition of these elements in the furnace or ladle being necessary. Mayari steel has given excellent satisfaction in a large number of cases, although it undoubtedly is not equal to synthetic chrome nickel steel where the highest quality chrome nickel steel is required.

In the natural or forged condition Mayari steel has from 8000 to 10,000 lbs. per square inch higher tensile strength and elastic limit than a carbon steel of the same carbon content. Like all alloy steels, it welds with more or less difficulty by the ordinary methods, and would not be recommended for purposes where a welded part is subject to great strains. By careful work in a Thompson electric welding machine, excellent results are obtained, so that where this method is applicable Mayari steel may be welded satisfactorily.

The physical properties of Mayari steel, heat treated, in  $\frac{7}{8}$  in. bars, are shown in Figs. 191, 192 and 193. The effect on the physical properties of variation in the size of the piece treated is indicated in the charts, Figs. 194 and 195, which show the properties of heat-treated rounds from 1 in. to 6 ins., and  $\frac{7}{8}$  in. to  $4\frac{1}{2}$  ins. diameter, respectively. All of the rounds on the same chart were from the same heat of steel. These were treated together at the same time in exactly the same manner. The first chart is 0.28 per cent. carbon, and the second 0.39 per cent. carbon; both grades contained 0.45 per cent. chrome with the usual nickel. On the bars over 2 ins. in diameter the tests were taken one-half the distance from the center to the outside, and on the smaller rounds they were taken from the center.

The following table<sup>1</sup> shows the approximate difference in drawing temperatures for Mayari steel of larger sizes than those given on the charts of Figs. 191 to 193. When it is desired to obtain the same elastic limit on a size larger than  $\frac{7}{8}$ -in. diameter, find the drawing temperature on the chart, then by making the allowance given in the table below for the size desired, the proper temperature for this elastic limit will be determined. The other properties will vary from those on the chart by the percentage shown in the table.

Diameter.	Change in Drawing Temperature.	Physical Properties; Per Cent. of that given on Charts for $\frac{7}{8}$ -in. Rounds.			
		Tensile Strength, Per Cent.	Elastic Limit, Per Cent.	Elongation, Per Cent.	Reduction of Area, Per Cent.
$\frac{7}{8}$ in.	0	100	100	100	100
$2\frac{1}{2}$ ins.	- 90° F.	102	100	90	96
$3\frac{1}{2}$ ins.	- 135° F.	110	100	87	85
$4\frac{1}{2}$ ins.	- 235° F.	122	100	80	83

<sup>1</sup>Penna. Steel Co.



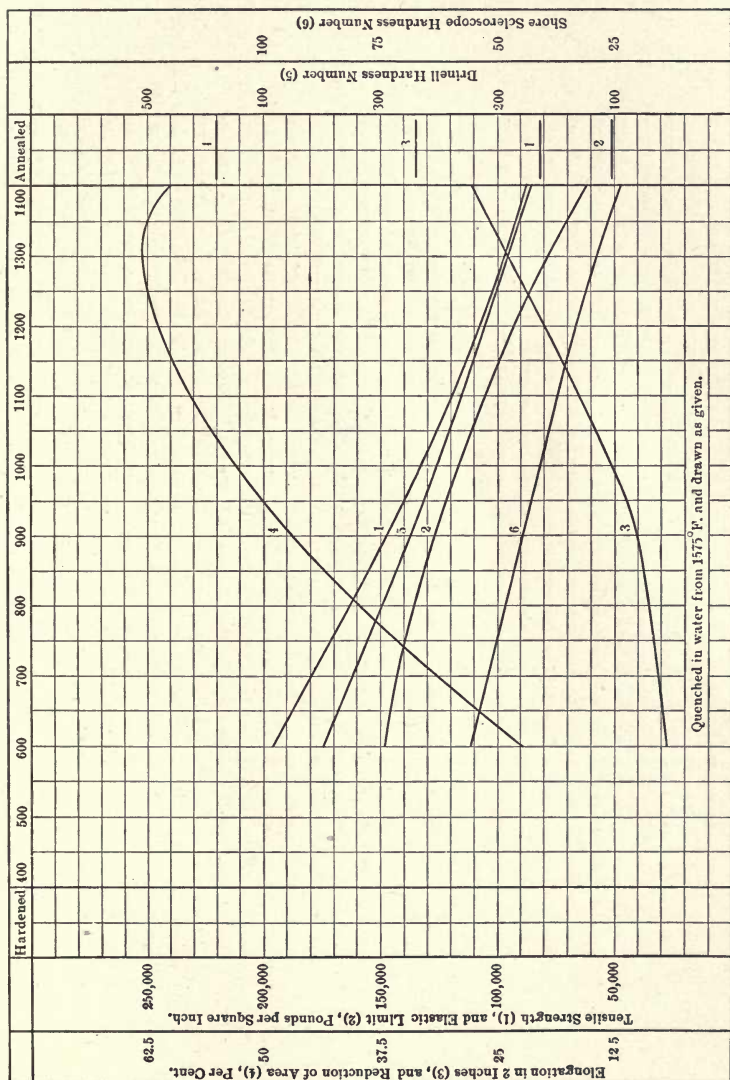


Fig. 191.—Normal Characteristics of 0.20 Carbon, Mayari Chrome Nickel Steel, Heat Treated.

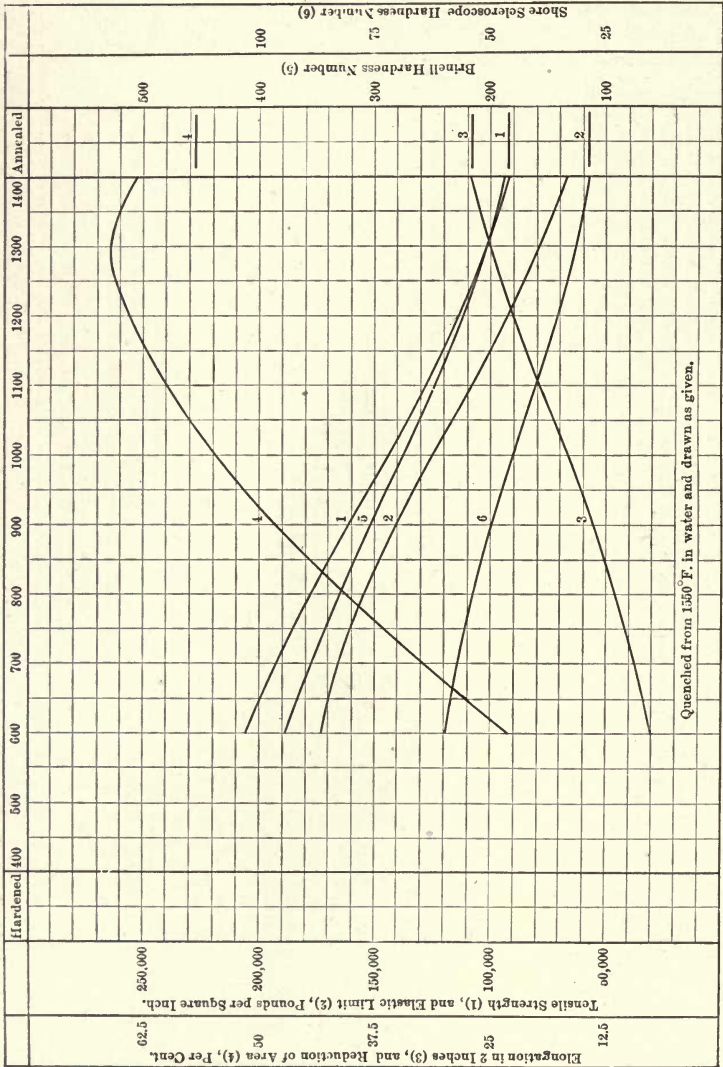


FIG. 192.—Normal Characteristics of 0.30 Carbon, Mayari Chrome Nickel Steel, Heat Treated.

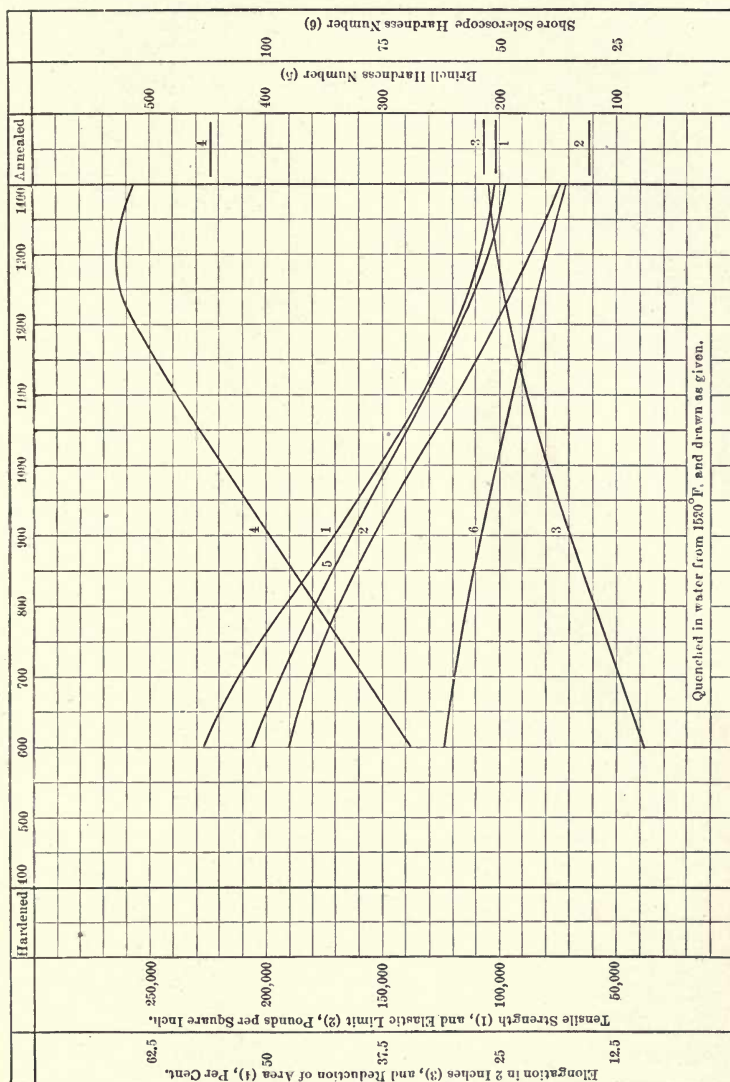


FIG. 193.—Normal Characteristics of 0.40 Carbon, Mayari Chrome Nickel Steel, Heat Treated.



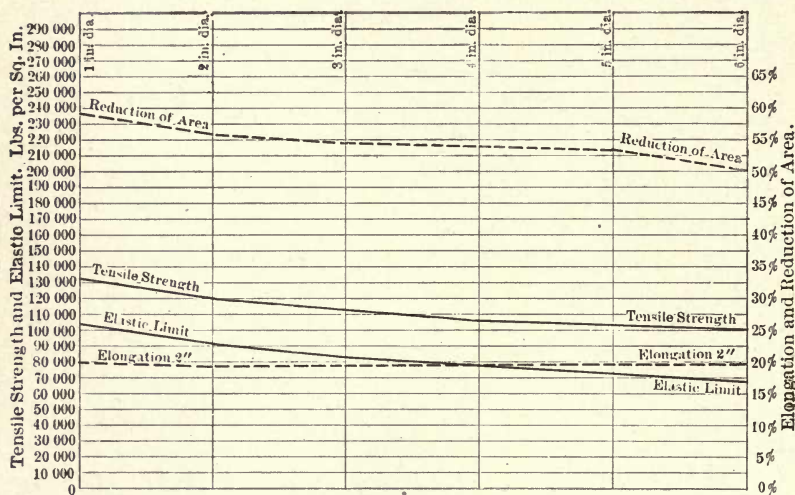


FIG. 194.—Effect of Size on Physical Properties of Mayari Steel, 0.30 Carbon. Same Analysis and Same Treatment, (Penna. Steel Co.)

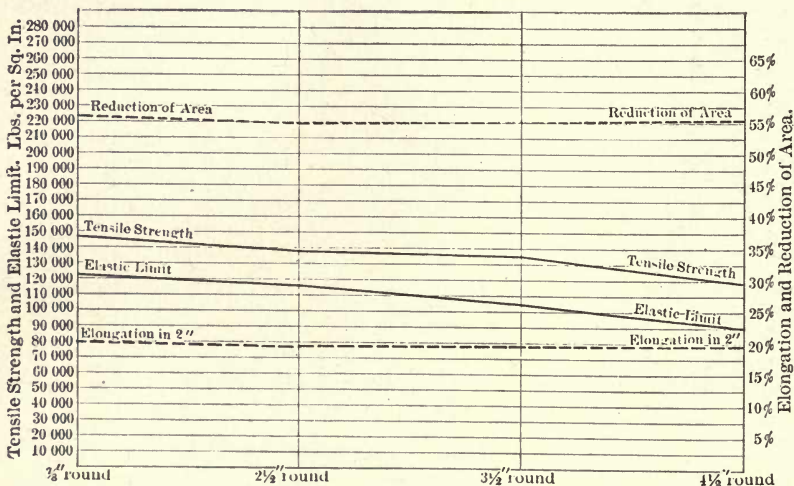


FIG. 195.—Effect of Size on Physical Properties of Mayari Steel, 0.40 Carbon. Same Analysis and Treatment, (Penna. Steel Co.)

## CHAPTER XIV

### VANADIUM STEELS

THE author approaches the general subject of vanadium steels with much hesitation. What has not been said about the merits or demerits of chrome vanadium versus chrome nickel is hardly worth mentioning; and many of the "facts" (or fancies?) put forth in the advocacy of one and the utter condemnation of the other should not be mentioned. Having had to do with the manufacture as well as the use of both, he feels that much may be said in favor of each, but that neither steel is the "one and only"—each has its specific sphere of usefulness and most advantageous application.

The principal effect of vanadium additions to steel is its effect upon the physical characteristics of the steel. Like most alloys, vanadium tends to give a finer and denser structure than that ordinarily obtained in straight carbon steels. In true vanadium steels, i.e., steels in which vanadium is present in definite commercial quantities, the general action of vanadium is similar to that of many of the alloys previously discussed, but it also presents other interesting phenomena. Vanadium, in the regular steels containing about 0.12 to 0.20 per cent. vanadium, is probably present in both the ferrite (similar to nickel) and also as a double carbide in the cementite (similar to chrome). In support of the first statement that vanadium is in solid solution in the ferrite are the results of many tests which appear to show that the ductility is higher in these commercial vanadium steels than in corresponding steels which do not contain vanadium. This is based on the assumption, generally accepted, that the nature of the ferrite element is indicative, to a large degree, of the ductility of the steel.

The proof direct that vanadium forms a double carbide is illustrated by steels with higher percentages of contained vanadium. Thus steels containing 0.2 per cent. carbon and up to 0.7 per cent. vanadium; or 0.8 per cent. carbon and 0.5 per cent. vanadium, are normally pearlitic; but any increase in the vanadium content over these limits will produce a characteristic double carbide component.

From these limiting ratios of carbon and vanadium it is evident that vanadium has a powerful influence upon the transformation ranges—more so, indeed, than any of the common alloying elements. This also goes to show the reason why only small quantities—0.25 per cent. vanadium or under—are necessary to produce a noticeable effect.

As a general proposition, any alloy which tends to form a cementitic compound in steel also has the tendency to require a higher temperature for quenching in order to bring the steel as a whole into a state of equalization. This was found to be true in the case

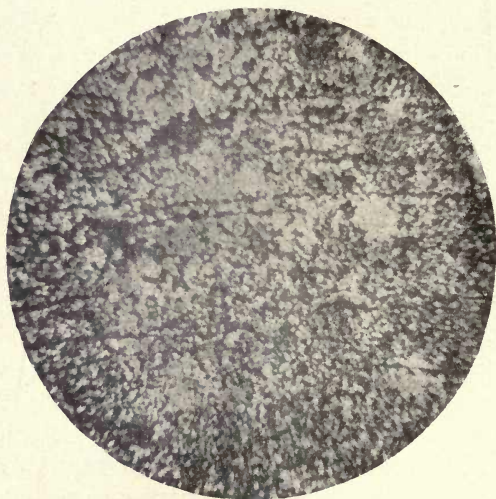


FIG. 196.—Chrome Vanadium Steel, Type A, Oil Treated at the Same Temperatures Used for a Corresponding Chrome Nickel Steel.  $\times 60$ . (Bullens.)

of chrome, and it is also true of vanadium steels. A study of the heat-treatment data subsequently given will show that vanadium alloy steels give the best results with an apparently abnormally high quenching temperature, or at about  $1560^{\circ}$  to  $1600^{\circ}$  F. for the medium carbon grades. This point is also illustrated by the photomicrograph in Fig. 196, which illustrates the structure of a rolled plate of "Type A" chrome vanadium steel oil treated at the temperatures best suited for a chrome nickel steel of the same carbon and manganese content. From the structure thus shown it is evident that the steel as a whole has not been equalized at the temperature for hardening ( $1500^{\circ}$  F.) which was used, since the



ferrite (white) is still segregated and tends to follow the lamellar structure of the original steel.

On the other hand, if we follow out the characteristics peculiar to most alloy steels of a carbide nature, we would expect that the vanadium steels would be inherently more sensitive to prolonged heating or rapid cooling. Now while it is true that steels containing vanadium will give a greater depth of hardness upon suitable quenching than will some steels of a ferritic nature (such as nickel steels), it does not appear to be true that vanadium abnormally increases the sensitiveness of the steel to prolonged heating. This appears to be one of the anomalies of vanadium steels.

Viewed from the standpoint of physical test values, vanadium requires the presence of another alloy as an "intensifier," in order that the full effect and influence of the vanadium additions may be felt. Just as chrome greatly intensifies the influence of nickel in steel, so chrome also seems to bring out the latent capabilities of vanadium, but to an even greater extent. Thus the majority of the vanadium steels now in commercial use are of the chrome vanadium type.

The predominant note which is always sounded when speaking or writing about chrome vanadium or vanadium steels is that of increased dynamic strength. There is little doubt but that vanadium greatly increases the dynamic strength in comparison with that of a corresponding straight carbon steel. Upon the relative merits, as regards dynamic strength, of chrome vanadium and chrome nickel steels, we have commented under the latter steels. Extensive tests made by the author to determine dynamic strength have led to varying results, and he deems it best to leave the subject with the warning given in the opening paragraph of this chapter.

The following equations connecting maximum strength, Brinell hardness number and scleroscope hardness number have been computed <sup>1</sup> from several hundred tests made with chrome vanadium of different carbon content and heat treated to bring out all possible physical properties:

$$(1) \quad M = 0.71 B - 29.$$

$$(2) \quad M = 4.2 \quad S - 21.$$

$$(3) \quad B = 5.5 \quad S + 27.$$

<sup>1</sup> R. R. Abbott, A. S. T. M., Vol. XV, Part II, 1915, p. 43 et seq.

$M$  = maximum strength in units of 1000 lbs. per sq. in.

$B$  = the Brinell hardness number.

$S$  = the scleroscope hardness number.

The maximum strength corresponding to different Brinell values as determined by equation (1) for these steels is as follows:

Brinell.	Maximum Strength, Lbs. per Sq. In.	Brinell.	Maximum Strength, Lbs. per Sq. In.
100	42,000	350	219,000
150	77,000	400	255,000
200	113,000	450	290,000
250	148,000	500	326,000
300	184,000	550	361,000

The maximum strength corresponding to different scleroscope values as determined by equation (2), and the corresponding Brinell numbers as determined by equation (3), for these steels, are as follows:

Scleroscope.	Maximum Strength, Lbs. per Sq. In.	Brinell.
20	63,000	137
30	105,000	192
40	147,000	247
50	189,000	302
60	231,000	357
70	273,000	412
80	315,000	467
90	357,000	522
100	399,000	577

Static test results<sup>1</sup> upon various "types" of vanadium steels follow:

<sup>1</sup> In part by the American Vanadium Co., Pittsburgh, Pa.

## TYPE "A" CHROME-VANADIUM STEEL

*Tests from Small Sections*

Carbon.....	.26%	Manganese.....	.48%
Chromium.....	.92%	Silicon.....	.06%
Vanadium.....		.20%	

Treatment.	Tensile Strength.	Elastic Limit.	Elongation in 2 Ins., %.	Reduction of Area, %.
As rolled.....	132,000	110,000	19.0	51.5
Annealed 1475° F....	83,700	61,000	34.8	66.4
Oil tempered:				
1650°-1155° F.....	133,000	99,020	30.0	69.9
1650 -1110 .....	137,000	112,000	20.0	61.0
1650 -1020 .....	141,500	123,000	18.0	63.5
1650 - 930 .....	162,700	146,250	15.0	57.0
1650 - 840 .....	177,500	151,500	14.0	53.0
1650 - 750 .....	183,500	155,000	13.0	51.0
1560 -1155 .....	131,000	100,000	28.0	67.0
1560 -1110 .....	133,000	108,400	17.5	65.4
1560 -1020 .....	137,500	112,750	21.0	64.5
1560 - 930 .....	156,800	138,440	16.5	59.8
1560 - 840 .....	171,100	147,150	15.0	61.0
1560 - 750 .....	173,900	149,800	13.0	57.0
Water tempered:				
1650°-1155° F.....	156,000	133,000	18.0	62.5
1650 -1110 .....	160,900	149,700	16.0	60.4
1650 -1020 .....	167,800	151,000	12.0	53.6
1650 - 930 .....	183,200	166,800	12.5	56.5
1650 - 840 .....	204,800	176,200	12.5	54.5
1560 -1155 .....	153,050	136,600	27.0	60.0
1560 -1110 .....	156,500	146,300	17.0	61.0
1560 -1020 .....	166,800	149,100	14.0	58.9
1560 - 930 .....	176,950	165,000	14.0	59.0
1560 - 840 .....	201,800	172,800	12.5	54.5

*Tests from Medium Sections*

Carbon.....	.23%	Manganese.....	.58%
Chromium.....	.82%	Silicon.....	.105%
Vanadium.....		.17%	

Stock.	Treatment.	Tensile Strength.	Elastic Limit.	Elongation in 2 Ins., %.	Reduction of Area, %.
	Oil tempered:				
2½-in.	1650°-1050° F.....	125,730	108,950	19.0	60.4
2½-in.	1650 -1050 .....	124,160	106,000	20.0	60.6
2⅝-in.	1650 -1050 .....	122,740	104,750	19.5	57.0
2⅝-in.	1650 -1050 .....	126,700	111,500	17.0	53.0
2¾-in.	1650 -1050 .....	121,080	106,500	18.0	60.7
2¾-in.	1650 -1050 .....	124,130	107,000	18.5	61.1



*Test from 6-in. Tender Axle*

Carbon.....	29%	Manganese.....	28%
Chromium.....	1.00%	Silicon.....	.06%
Vanadium.....		20%	

Treatment.	Tensile Strength.	Elastic Limit.	Elongation in 2 Ins., %.	Reduction of Area, %.
Water tempered: 1690°-1155° F.....	115,000	90,000	21.0	55.0

*Tests from Locomotive Driving Axles, 10 Ins. Diameter**Average Test of 287 Heat-treated Axles*

Carbon.....	35%	Manganese.....	50%
Chromium.....	.90%	Vanadium.....	.22%

Elastic limit, pounds per square inch..... 81,600

Tensile strength, pounds per square inch..... 108,890

Elongation in 2 ins., per cent..... 21.75

Reduction of area, per cent..... 58.75

## TYPE "D" CHROME VANADIUM STEEL

*Tests on Small Sections*

Carbon.....	50%	Manganese.....	92%
Chromium.....	1.02%	Silicon.....	.065%
Vanadium.....		20%	

Treatment.	Tensile Strength.	Elastic Limit.	Elongation in 2 Ins., %.	Reduction of Area, %.	Brinell Hardness No.
As rolled.....	153,350	124,450	12.5	37.0	286
Annealed 1475° F....	103,440	63,660	25.8	61.5	187
Oil tempered:					
1650°-1110° F.....	186,800	170,000	15.5	45.2	340
1650 - 1020.....	201,150	186,100	13.0	45.5	364
1650 - 930.....	209,800	192,200	12.5	42.5	364
1650 - 840.....	227,040	217,360	10.0	35.5	402
1650 - 750.....	264,500	239,700	6.5	17.0	444
1600 - 1110.....	186,100	161,200	13.5	45.5	340
1600 - 1020.....	205,500	187,000	12.0	45.0	340
1600 - 930.....	214,050	203,600	11.5	43.0	380
1600 - 840.....	237,500	221,000	10.0	29.5	418
1560 - 1020.....	197,100	187,100	12.5	45.0	340
1560 - 930.....	214,270	201,400	11.5	36.0	418
1560 - 840.....	234,150	215,850	9.0	28.5	418
1560 - 750.....	261,850	240,000	7.0	22.0	418
1520 - 1020.....	183,500	177,250	14.5	47.5	340
1520 - 930.....	215,450	193,100	12.0	41.5	387
1520 - 840.....	237,750	213,400	10.0	35.5	387
1520 - 750.....	260,500	240,000	8.0	24.0	444

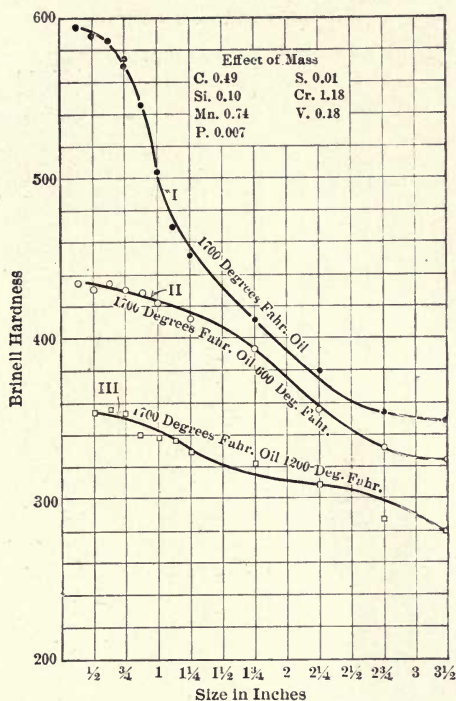


Fig. 197.—Effect of Mass upon the Hardness of Chrome Vanadium Steel.  
 (Matthews & Stagg.)

The effect of mass upon the hardness of steel of this type is shown in Fig. 197.<sup>1</sup>

#### TYPE "G" CHROME VANADIUM STEEL

Carbon.....	.60%	Manganese.....	.54%
Chromium.....	.88%	Silicon.....	.175%
Vanadium.....	.19%		

Treatment.	Tensile Strength.	Elastic Limit.	Elongation in 2 ins., %.	Reduction of Area, %.	Brinell Hardness No.
Oil tempered:					
1650°-1110° F.....	205,190	179,300	13.0	37.0	402
1650 - 930 .....	240,400	220,000	10.0	28.3	477
1650 - 750 .....	273,000	248,660	8.0	27.3	532

<sup>1</sup> From Matthews and Stagg, "Factors in Hardening Tool Steel."

## NICKEL VANADIUM STEEL

Carbon.....	.29%	Manganese.....	.45%
Nickel.....	3.41%	Silicon.....	.090%
Vanadium.....		.20%	

Treatment.	Tensile Strength.	Elastic Limit.	Elongation in 2 ins., %.	Reduction of Area, %.
Annealed 800° C.....	107,300	73,000	23.5	55.5
Oil tempered:				
1600°-1160° F.....	148,300	126,250	18.0	58.0
1600 - 1110 .....	150,000	128,500	17.5	57.4
1600 - 1020 .....	151,500	132,500	16.0	56.9
1600 - 930 .....	162,000	144,200	14.5	52.6
1600 - 840 .....	178,200	157,210	13.0	52.7
1600 - 750 .....	193,200	163,000	12.0	50.2
1520 - 1160 .....	137,700	123,000	16.0	59.0
1520 - 1110 .....	140,700	125,500	17.5	54.2
1520 - 1020 .....	148,100	126,800	16.5	55.0
1520 - 930 .....	154,900	135,000	15.5	57.2
1520 - 840 .....	165,800	146,500	14.0	55.2
1520 - 750 .....	181,000	162,800	14.0	53.5
Water tempered:				
1600°-1160° F.....	148,000	126,700	18.5	58.1
1600 - 1110 .....	153,800	133,100	15.0	58.8
1600 - 1020 .....	156,300	136,500	14.0	54.5
1600 - 930 .....	161,200	146,700	14.5	56.4
1600 - 840 .....	186,400	173,300	13.0	52.7
1600 - 750 .....	195,200	176,580	12.0	52.2
1520 - 1160 .....	139,800	128,570	18.5	59.7
1520 - 1110 .....	146,000	132,250	14.0	57.5
1520 - 1020 .....	154,600	133,900	15.5	56.3
1520 - 930 .....	160,400	144,600	15.0	51.7
1520 - 840 .....	184,500	176,750	13.0	53.0
1520 - 750 .....	199,300	182,700	12.0	50.0



GENERAL RESULTS FROM HEAT TREATING CHROME VANADIUM STEELS

Approximate Chemical Composition.				Approx. Heat Treat.		Minimum Physical Results after Treatment.			
Carbon.	Manganese.	Chrome.	Vanadium.	Quench, Deg. F.	Draw, Deg. F.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation, in 2 Ins. Per Cent.	Reduction, of Area, Per Cent.
0.18-0.25	0.35-0.50	0.60-0.80	over 0.16	1650 water	930	90,000	70,000	22	50
0.25-0.32	0.40-0.60	0.80-1.00	over 0.16	1650 water	1300	60,000	40,000	35	65
0.32-0.37	0.40-0.50	0.80-1.00	over 0.16	1650 water	930	110,000	85,000	18	45
0.35-0.43	0.70-0.90	0.80-1.10	over 0.16	1650 water	1300	85,000	60,000	28	60
0.43-0.52	0.70-0.90	0.80-1.10	over 0.16	1650 water	930	150,000	130,000	14	45
0.52-0.60	0.60-0.80	0.80-1.10	over 0.16	1650 water	1300	95,000	65,000	24	60
				1650 water	930	170,000	150,000	12	40
				1650 water	1300	110,000	75,000	20	55
				1650 water	930	185,000	160,000	10	40
				1650 water	1300	120,000	85,000	18	50
				1650 water	930	200,000	180,000	8	35
				1650 water	1300	130,000	100,000	20	50

## CHAPTER XV

### MANGANESE, SILICON AND OTHER ALLOY STEEL

#### MANGANESE STEELS

THE term "manganese steel," by commercial usage, generally refers to steels with that high percentage of manganese which will cause the metal to become austenitic under the conditions of ordinary cooling or suitable heat treatment. But before proceeding to a discussion of such steels, it is desirable to amplify the remarks we have previously made upon the subject of pearlitic manganese steels.

#### PEARLITIC MANGANESE STEELS

It is a well-known fact that manganese in these steels adds considerably to the tensile strength; this beneficial effect is further dependent upon the percentage of carbon, as has been previously shown. On the other hand, the effect of manganese in normally pearlitic manganese steels upon the fragility of the steel is a more or less undetermined factor. Many persons have undoubtedly confused the subject of inherent brittleness or non-resistance to shock with the results caused by the sensitiveness of these steels to certain heat-treatment methods. They have assumed, because a piece of steel with 1 to 2 per cent. manganese may have cracked on drastic water quenching, that the steel was "brittle," when, as a matter of fact, this result was probably due to reasons entirely apart from the dynamic strength of the metal. Thus it may be said that this situation has led to the belief that manganese contributed an embrittling effect to the steel. Even assuming that such an influence *may* exist in the case of very high-carbon steels, it distinctly has not been proven to be true of the hypo-eutectoid steels. In fact, there is now considerable evidence which tends to show that the lower-carbon pearlitic manganese steels, *when properly made and suitably heat treated*, are *not* brittle. If the steel is made in small heats, has been thoroughly refined, and with the elimination of impurities to

a minimum, the author believes that a great deal may be accomplished with such steels.

With steel made by the ordinary open-hearth process, it should be remembered that the presence of any considerable amount of manganese, such as 1 per cent. or more, has the tendency to increase the *sensitiveness* of the steel in its response either to prolonged heating at temperatures above the critical range, or to rapid cooling from such temperatures. Thus high temperatures of annealing will increase the grain size very rapidly; while high carbon may cause the steel to fracture when water quenched.

On the other hand, certain manganese steels with 1.5 to 2 per cent. manganese and a considerable carbon content, made in the electric furnace, have shown wonderful mechanical properties, and, in addition, will stand a tremendous amount of abuse in their thermal treatment without any great ill effects. Granting that the electric furnace is capable of producing a higher grade of steel than other processes now in use, it must nevertheless be evident that a large proportion of the merits of these pearlitic manganese steels must be due to the inherent influence of the manganese itself.

In treating pearlitic manganese steels it should be remembered that each 0.1 per cent. manganese will lower the critical range on heating by about  $5^{\circ}$  to  $6^{\circ}$  F., so that lower temperatures may, and in most cases should, be used for their hardening or full annealing. In general, the effect of manganese on the critical ranges is about twice that of nickel.

#### HIGH-MANGANESE STEELS

In general, the requirements for producing a commercial manganese steel necessitate a manganese content of about 6 or 8 per cent. to 20 per cent., in combination with the proper amount of carbon. Below the lower limits given, the steel, even by the most suitable treatment, may be characterized by the presence of weak and brittle martensite. The upper limits are determined by the cost of the manganese additions, and further, by the again predominating influence of the carbon content (when the manganese rises to around 20 per cent.), which will make the steel stiff and brittle when cold. Most manganese steels will have about 11 or 12 per cent. manganese and about 1.0 to 1.2 per cent. carbon.

Recent research work along the lines of determining the proper combination of carbon and manganese has greatly widened the commercial range for the manganese content, so that the more



recent steels have the tendency toward a percentage of manganese lower than that originally thought necessary. Similarly, the field for the use of high manganese steels has also been considerably broadened. Above all, however, the peculiar merit of these steels lies in the resistance to abrasive wear, in combination with sufficient strength and ductility. In this regard, manganese steels appear to resist the abrasive wear characteristic of heavy impacts of hard substances better than that caused by the sliding attrition of hardened parts, or like that of an abrasive wheel.

Aside from the dynamic strength, the selection of a manganese steel for any specific work depends upon the correlation of wearing qualities and static properties. In general, and in connection with a maximum wear resistance, it may be said that the most ductile steel which will give an elastic limit sufficiently high to avoid distortion in service will be best. And these, in turn, depend upon the proper combination of carbon and manganese. Thus a steel with 9 to 11 per cent. manganese and the proper amount of carbon will have a higher elastic limit than a steel with over 11 per cent. manganese. Again, steel with 11 per cent. manganese and 1.10 per cent. carbon will have a higher elastic limit than a steel with 15 per cent. manganese and 0.8 per cent. carbon. With high manganese and low carbon, steels quenched in water from 1830° F. will give a low elastic limit and a flow of metal which may prove excessive for many duties. A great deal also depends upon a suitable heat treatment of the steel.

As might be expected from our knowledge of the influence of the rate of cooling upon the structure of high-alloy steels, the physical properties of these high-manganese steels are greatly modified by the method of casting, the size of the casting, and the mechanical elaboration. The first two factors in particular have a great influence upon the toughness of the metal. The average tests of commercial manganese steels with about 11 or 12 per cent. manganese and a little over 1.0 per cent. carbon will give approximately the following:

Condition of the metal.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation, % in 2 Ii s.
Cast.....	82,000	45,000	30
Rolled.....	135,000-140,000	60,000-70,000	30-40
Forged.....	142,000	55,000	38

The elastic limit of some sections as rolled may even go as high as 75,000 lbs. per square inch; the proper heating and working of the

metal plays a very important part in the results to be obtained on physical test.

A common specification for manganese steel rails is as follows:

Chemical:

Carbon, per cent.....	0.95 to 1.15
Manganese, per cent.....	10 to 13
Silicon, per cent.....	0.20 to 0.40
Phosphorus, per cent.....	under 0.10
Sulphur, per cent.....	under 0.06

Physical:

Tensile strength, lbs. per sq. in.....	100,000
Elastic limit, lbs. per sq. in.....	55,000
Elongation in 2 ins., per cent.....	20

Small amounts of chrome are sometimes added to increase the elastic limit, so that in rolled sections the elastic limit will often be as high as 85,000. It is stated that the resistance to shock is not apparently lowered by the addition of chrome up to 1 per cent., but with chrome above 0.5 per cent. the elongation is rapidly decreased, and with chrome above 1 per cent. the elongation falls below 20 per cent. in 2 inches.

The heat treatment of high-manganese steels presents a most important phase in connection with the successful application of these steels. Incorrect treatment is responsible for many of the failures which have been registered against manganese steels, and usually has been caused either by a mistaken idea of the particular structure best suited to the specific work in hand, or by a lack of sufficient knowledge of the mechanics of the austenite transformation. The use of the microscope, and a judicious consideration and application of the results obtained, are probably the best means of solving a given problem in connection with heat-treatment adjustments.

This thermal treatment for the majority of these steels involves two distinct, though correlated factors: (1) The change of grain size, and (2) the relationship of austenite and carbide, with or without the presence of martensite. As the principal manganese steels now used in commercial practice do not naturally contain martensite, nor is it generally wanted, its consideration may be omitted.

The necessity for the first requirement should be obvious: commercial high-manganese steel *as cast* is fundamentally austenitic;

the crystals are often excessively large, and in many instances form a weak, columnar structure. It is evident that such a steel, for many purposes, will be entirely unsatisfactory.

On the other hand, many high-manganese steels as forged, are characterized by an exceedingly fine, almost chalky structure, and yet may be very brittle. If a bar of manganese steel should be heated to 1800° F., and one half be allowed to cool slowly and the other half quenched in water, both ends will have a comparatively fine structure or grain size, yet the slow-cooled end will have but 2 to 4 per cent. elongation as against 50 to 60 per cent. elongation in the quenched end.



Fig. 198.—Commercial Manganese Steel Annealed at 1750° F.  
×100. (Bullens.)

Although annealing will effect a change in the grain size, to a greater or lesser extent, it will also have a far-reaching, vastly more important, and injurious result—and we intentionally omit any reference to the tendency which certain compositions might have to become martensitic on very slow cooling. This effect of annealing is due to the formation, on very slow cooling, of the maximum amount of carbide—an extremely hard and brittle manganitic cementite rejected by the austenite, and which forms as a weak membrane around the austenite grains, as spines and needles, or in other characteristic manner. This is shown in the photomicrograph in Fig. 198, taken from a rolled commercial manganese steel



and then annealed at 1750° F. The effect of annealing upon the physical properties is shown by the following table of results, obtained from tests upon annealed manganese steels:

HIGH-MANGANESE STEELS, ANNEALED.

Carbon, Per Cent.	Manganese, Per Cent.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation in 2 Ins., Per Cent.	Reduction of Area, Per Cent.
0.95	10.07	94,600	67,500	1	1.4
1.00	11.21	99,950	77,660	1	0.75
1.07	13.38	103,670	62,350	3	3.4

Annealing these high-carbon manganese steels is obviously illogical, and it is the carbide which is the main source of the difficulty. And yet a large proportion of the peculiar and distinctive wearing qualities of these steels is probably due to the manganitic carbide, although in a form other than that just described.

On heating to a high temperature the carbide membrane produced by slow cooling, or the carbide segregations, are gradually taken into solution by the austenite; and by rapid cooling from that same temperature the carbide is more or less prevented from reprecipitating, and especially from taking on that enweakening structure (i.e., as a membrane or segregations) previously mentioned. Since the carbide originally formed in casting is very sluggish in its response to heat in being absorbed by the austenite (as is also a characteristic more or less marked in all hyper-eutectoid steels), and as the equalization of the steel as a whole also takes place slowly, a high temperature is necessary. Further, the temperature must also be high, and the cooling be effected very rapidly—such as water quenching—to retain the carbide in solution. Such a treatment will give the most ductile steel. The temperature required is generally not less than 1830° F. Thus a water quenching from 1830° F. of the annealed steels previously given will show a tensile strength of about 135,000 to 145,000 lbs. per square inch, with an elongation of 50 to 60 per cent.

On the other hand, by varying the factors of temperature, duration of heating, and rate of cooling, it is possible to obtain physical properties covering a wide range. The static strength and ductility are largely governed by the amount of the original free carbide which is taken into solution and there retained by water quenching. Thus the properties of the steel, looking at the results of heat

treatment from this point of view, may be varied from that characteristic of the steel as cast, rolled, or forged, to that indicative of a full "water toughening."

There is another possible development of scientific heat treatment, however, which the author believes has not been fully noted—not even by some manufacturers of high-manganese steel itself. And by this is meant a treatment which will "spheroidalize" the carbide. The application of such a process as applicable to straight carbon steels, and the superior qualities thereby resulting in resistance to wear as relative to case-hardening work, have been discussed under Chapter VII. A microscopic examination of many properly treated high-tungsten steels will show a similar spheroidalizing action, and to which many of the mechanical properties of these steels may be due—even though the exact relation of cause and effect may not be known. And so certain processes may be worked out (or so the author is led to believe) for these high-manganese steels, in which resistance to wear is the main result desired. Based upon theory, and upon partly developed experiments, the author offers the above merely as suggestions.

In conclusion, the author would call attention to the fact that high-manganese steel has no critical or transformation points or ranges. Thus while in the ordinary steels the heat treatment is more or less guided by such temperatures, in high-manganese steels the only criterion of proper temperatures is the relation of the carbide to the physical properties: the absorption, with or without the precipitation, of such carbide, is the underlying basis for heat-treatment adjustment.

#### SILICON AND SILICO-MANGANESE STEELS

The use of silicon in commercial steels is practically confined to two classes: (1) a medium carbon and about 1.50 per cent. silicon, for use in tempered gears and springs—known as silico-manganese steel; and (2) a nearly carbonless steel with up to 3.50 per cent. silicon, for use in electrical apparatus.

The manufacture of silico-manganese steels in the open hearth must be carefully watched on account of their great tendency to piping and segregation, and a large discard must be made in the cropping of the ingots to insure good steel. Silico-manganese steels have considerable popularity among the foreign automobile manufacturers; their use in this country, however, is usually limited to the lower-priced cars. Although the lower cost favors their use,

their great sensitiveness to heat treatment and feeble resistance to shock limits their field of usefulness. But when handled with great care the silico-manganese (and also the silico-chrome) steels will give good results in works well equipped for obtaining accurate results in their heat-treatment operations. The temperature limits for quenching are narrower than for most alloy steels, and the steel responds altogether too quickly to variations in heating and cooling. Although these steels will give high static test results upon suitable treatment, the brittleness which is inherent to this type of steel usually proves the governing factor.

A typical American analysis for silico-manganese steel for gears and springs is as follows:

Carbon, per cent.....	0.43 to 0.53
Manganese, per cent.....	0.50 to 0.70
Silicon, per cent.....	1.25 to 1.50

Upon suitable treatment, usually a quenching in oil from about 1550° to 1600° F., followed by tempering to suit the requirements, the following results are representative:

Tensile strength, lbs. per sq. in....	195,000 to 230,000
Elastic limit, lbs. per sq. in.....	175,000 to 220,000
Elongation, per cent. in 2 ins.....	12 to 8

The tables (taken from a work by Revillon) on page 352 give some characteristic French and German gear steels of the silicon-manganese type, together with their physical properties. Steel No. 6 (a straight carbon steel) is given for comparison, and was designed to do away with the reheating or tempering necessary with the high-silicon steels; it is reported that tests on the untempered gears gave very satisfactory results.

As a side-light on the effect of certain treatments of pieces of large section of silico-manganese steel, the following may be of interest. The author recently made some experiments with a characteristic steel, 5 ins. in diameter, and analyzing 0.44 per cent. carbon, 0.60 per cent. manganese, and 1.50 per cent. silicon. The purpose was to determine the possibility of using this steel in place of a 0.60 per cent. chrome steel with approximately the same manganese and carbon content. The principal requirement to be met was to obtain a glass-hard surface such as could be obtained with the chrome steel. It was found that the hardness requirement could not be met with the silico-manganese steel, and more important,



that the steel would often split or crack when quenched in either the cold water or brine bath used for the chrome steel.

## EXPERIMENTS WITH SILICO-MANGANESE GEAR STEELS

No.	Chemical Analysis.			Annealed at 1650° F.					
	Carbon.	Manganese	Silicon	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation, %	Reduction of Area, %	Brinell Hardness.	Shock Test.
1	0.40	0.57	1.89	105,820	68,410	19	40	207	36.1
2	0.57	0.61	1.22	127,860	74,100	15	29	225	21.7
3	0.50	0.64	1.64	123,450	82,490	12.5	21	215	32.5
4	0.70	0.78	1.87	142,510	80,790	15.5	35	241	23.3
5	0.39	0.52	1.98	109,230	78,510	20	43	203	43.4
6	0.45	0.42	0.43	87,760	48,780	19.5	51	197	43.4

Quenched oil from 1520° F., drawn at 930° F.*						
No.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation.	Reduction of Area.	Brinell Hardness.	Shock Test.
1	178,380	159,300	4.5	12	315	39.8
2	219,460	204,500	5.5	15	467	25.3
3	156,450	136,830	4	19	307	75.9
4	210,500	197,700	2.5	17	435	47
5	135,120	107,810	11	43	274	47
6	278,770	271,660	3.1	14	422	39.8

\* Nos. 5 and 6 were quenched from 1560° F.; No. 6 was drawn at 400° F.

The critical ranges of No. 5 were: Ac, 1560°; Ar, 1410°. For No. 6, Ac, 1420°; Ar, 1290°.

The most important use for straight silicon steels is that for electromagnets and for other electrical purposes demanding a high magnetic permeability or electrical resistance. Hadfield's silicon steel, containing approximately 2.75 per cent. silicon, and with carbon, manganese and the other impurities as low as possible, is representative of this class. His treatment for this steel consists of first heating it to about 1950° F. and cooling quickly, and then heating to 1380° F. and cooling very slowly, and which is sometimes followed by a reheating to 1475° F. and cooling very slowly.

Another silicon steel, used in place of dynamo sheet iron, specifies similar carbon, manganese, etc., but with a silicon content of about 3.25 per cent. The thermal treatment recommended for this steel is a thorough heating at about 1430° to 1475° F., followed by very slow cooling.

## TUNGSTEN STEELS

The pearlitic low-tungsten steels when quenched from the proper temperature do not appear to be any more modified by this quenching than are the corresponding straight carbon steels; the effect of tungsten in such steels is, however, to increase the tensile strength, with the degree of brittleness remaining about the same. For this reason tungsten is sometimes used in place of silicon—which has a feeble resistance to shock—for springs. The following table gives the analysis and physical properties of a characteristic low-tungsten spring steel:

Carbon.....	0.45%	Silicon.....	0.30%
Manganese.....	0.22%	Tungsten.....	0.60%

	Annealed.	Quenched in Oil from 1560°, Drawn at 930° F.
Tensile strength, lbs. per sq. in. ....	113,500–121,000	185,000
Elastic limit, lbs. per sq. in. ....	85,000	128,000
Elongation, per cent. ....	14	7

The use of tungsten for ordinary structural purposes is mainly limited by the fact that such steels have to be made by the crucible process.

The other, and most important uses for tungsten, are those for permanent magnets (the steel usually being used in the hardened condition), and for various varieties of tool steels in both high-speed and water- or oil-hardening types. Since these steels involve such a multitude of analyses and treatments, and form a subject of their own, it has been deemed best to omit any further discussion, but to refer the reader to works already published.

## MOLYBDENUM STEELS

On account of its high cost the use of molybdenum has been largely confined to high-speed and similar steel—and even there it has usually been superseded by tungsten. In the lower percentages, molybdenum may be present in steel as a fairly easily decomposable iron-molybdenum compound; with larger amounts of both molybdenum and carbon it is generally believed that the molybdenum forms a double carbide in a similar manner to chrome.

In the pearlitic molybdenum steels the influence of molybdenum is much like that of chrome, in that it increases the tendency to

greater hardness with proper quenching or with cold work, and likewise to increased brittleness upon prolonged heating at high temperatures. On the other hand, the molybdenum steels have a markedly higher ductility and toughness, besides an increased dynamic strength. The best results (disregarding its use for tools) have been obtained with the use of 1 to 2 per cent. molybdenum, in combination with the proper proportion of carbon—the carbon having a marked influence upon the physical properties of molybdenum steels. Considerable experimentation has been carried out with pearlitic molybdenum steels for rifle barrels and large guns; it has also been used in high-duty machine parts such as propeller-shaft forgings. It is reported that excellent results have been obtained in case-hardening steels with about 1 per cent. molybdenum.

The influence of molybdenum depends largely upon the heat treatment, as is shown in the following series of tests by Giessen with steels containing 1, 2, 4, and 8 per cent. molybdenum:

## 1.00 PER CENT. MOLYBDENUM STEEL

No.	Chemical.		As Rolled.			
	C.	Mo.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation, Per Cent. in 2 Ins.	Reduction of Area Per Cent.
1	0.195	1.03	67,040	44,800	33.31	64.32
2	0.445	1.05	108,800	78,800	19.5	49.23
3	0.87	1.02	160,000	104,000	14.5	34.36
4	1.215	1.10	117,340	.....	1.0	2.02

*Annealed*

No.	Tensile Strength, Lbs. per Sq. in.	Elastic Limit, Lbs. per Sq. In.	Elongation Per Cent. in 2 Ins.	Reduction of Area, Per Cent.	Bend Test, Deg.	Alternating Str'gth	Brinell Hard- ness.	Sclero- scope Hard- ness.
1	52,300	27,800	35.5	65.75	180	336	99	11
2	71,420	38,720	25.0	39.2	180	210	131	13
3	108,100	52,000	17.22	22.25	67	103	228	23
4	85,300	52,100	5.55	7.5	25	14	207	22

*Heat Treated (Hardened in oil, reheated to 1025° F.).*

1	90,100	47,150	27.46	68.4	180	301	241	27
2	210,560	168,600	14.08	49.2	180	137	387	37
3	240,490	193,700	9.15	25.2	16	92	418	44
4	279,000	203,900	4.92	12.0	34	71	512	45



# MANGANESE, SILICON AND OTHER ALLOY STEELS 355

## 2.00 PER CENT. MOLYBDENUM STEEL

No.	Chemical.		As Rolled.			
	C.	Mo.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs per Sq. In.	Elongation, Per Cent. in 2 Ins.	Reduction of Area, Per Cent.
5	0.246	2.176	117,820	.....	21.05	57.0
6	0.442	2.181	150,980	.....	16.7	46.41
7	0.883	2.186	198,910	124,250	12.1	32.07
8	1.21	2.109	216,830	169,340	7.04	9.6

## Annealed

No.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation Per Cent. in 2 Ins.	Reduction of Area, Per Cent.	Bend Test, Deg.	Alternating Str'gth	Brinell Hard- ness.	Sclero- scope Hard- ness.
5	65,070	31,580	33.3	62.5	180	370	116	15
6	82,300	43,400	27.7	44.3	180	259	143	18
7	107,070	54,770	18.8	27.5	100	126	207	22
8	95,200	61,710	9.4	13.5	43	27	196	22

## Heat Treated (Hardened in oil, reheated to 1025° F.).

5	171,140	115,400	15.49	54.4	180	172	387	35
6	211,460	149,100	14.08	47.2	180	103	444	39
7	260,800	178,800	5.63	12.0	26	80	512	47
8	270,940	.....	.....	.....	16	39	512	48

## 4.00 PER CENT. MOLYBDENUM STEEL

No.	Chemical.		As Rolled.			
	C.	Mo.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation, Per Cent. in 2 Ins.	Reduction of Area, Per Cent.
9	0.19	4.11	119,120	75,370	21.70	52.71
10	0.487	4.01	188,160	120,060	13.5	33.81
11	0.865	4.00	230,270	.....	8.0	17.27
12	1.06	4.02	239,230	179,900	10.56	18.40

*Annealed*

No.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation, Per Cent. in 2 Ins.	Reduction of Area, Per Cent.	Bend Test, Deg.	Alternating Str'gh	Brinell Hardness.	Scleroscope Hardness.
9	63,390	31,470	42.7	72.5	180	366	116	17
10	77,060	42,220	28.3	52.0	180	247	143	18
11	94,300	45,920	20.5	34.0	180	146	179	20
12	92,960	42,560	15.5	20.5	94	66	196	23

*Heat Treated (Hardened in oil, reheated to 1025° F.)*

9	88,180	66,500	30.20	64.0	180	329	286	28
10	188,900	139,780	11.26	41.6	123	109	444	43
11	258,050	203,940	4.22	4.8	56	52	512	44
12	282,240	267,000	7.04	23.2	4	45	532	48

## 8.00 PER CENT. MOLYBDENUM STEEL

No.	Chemical.		As Rolled.			
	C.	Mo.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation, Per Cent. in 2 Ins.	Reduction of Area, Per Cent.
13	0.135	8.01	92,290	.....	25.7	52.22
14	0.361	8.17	148,290	.....	19.4	45.9
15	0.445	8.11	215,040	154,110	19.71	34.0
16	0.775	7.85	193,890	149,090	9.85	18.4
17	1.125	7.92	245,500	189,950	8.45	16.4

*Annealed*

No.	Tensile Strength, Lbs. per Sq. In.	Elastic Limit, Lbs. per Sq. In.	Elongation, Per Cent. in 2 Ins.	Reduction of Area, Per Cent.	Bend Test, Deg.	Alternating Str'gh	Brinell Hardness.	Scleroscope Hardness.
13	79,070	41,660	31.1	58.75	180	283	143	16
14	77,060	34,720	36.6	68.23	180	273	143	18
15	83,220	38,640	32.2	57.5	180	215	156	18
16	87,580	45,140	22.2	35.5	171	108	170	20
17	92,290	48,830	16.1	24.0	85	66	187	22

*Heat Treated (Hardened in oil, reheated to 1025° F.)*

13	82,080	53,760	30.9	65.6	180	239	163	15
14	105,350	75,450	25.3	54.4	180	226	351	30
15	127,400	77,800	21.1	49.2	180	122	444	39
16	247,300	216,830	7.74	23.2	34	33	512	42
17	.....	.....	.....	.....	4	24	512	46

## CHAPTER XVI

### TOOL STEEL AND TOOLS

THE problem of selecting a proper grade of steel in relation to the work required is one hitherto met by the steel manufacturer alone. Until recently he has recommended this or that steel for a given requirement, depending more or less upon his general knowledge of the purpose for which the tool is to be used, and upon the experience of his customers in the past. But with the entrance of the technical man into manufacturing concerns and the great improvements resulting therefrom, a fuller knowledge of various steels, their composition, applicability and efficiency has been demanded. This has resulted in a wider dissemination of information regarding the physical, chemical and mechanical properties of steels manufactured by various steel companies, and a corresponding education of both maker and buyer.

**Grade.**—For the aid and information of their customers, the steel maker usually groups his tool-steel products into various “grades” and “tempers.” The former term refers to the “quality” of the steel, according to the class of raw material which has been used, together with the skill and care taken in producing the finished material. The highest grades should be used for tools operating under severe working conditions, demanding great endurance and resistance to torsional or other strains, or upon which a large labor cost has been placed. These conditions, such as are found in expensive dies, milling cutters, taps, etc., would require a high-grade steel. For such purposes as mill-picks, cheap tools, etc., it would be folly to use any but a lower-quality steel. Wear, the cost of redressing, regrinding and heat treatment are other factors which must be considered in the selection of the proper and most economical steel which will give the greatest efficiency in all senses of the word. With this in mind, the following brief synopsis is given:

1. Finest tools and dies: expense for material the smallest item entering into the cost and upkeep of the finished tool;
2. Finishing tools for lathe and planer work; special taps,



reamers, milling cutters and other similar tools requiring a high-grade steel; wood-working and corrugating tools;

3. General tool purposes;

4. Ordinary purposes, such as chisels, smith and boiler shop work, etc.

5. For rough or heavy work.

Expressing this in a different way, we may say that the choice of a grade of tool steel depends upon three factors:

1. The precision of the work required of the tool;

2. The relative cost of the steel in comparison with the labor involved in the manufacture of the tool;

3. The life of the finished tool and its relation to the cost of production.

**Temper.**—Carbon tool steels are further denoted by the “temper.” In tool-steel sales parlance this refers to the percentage of carbon in the steel and may be denoted by figures or letters. Such classifications generally refer to a 10-point carbon limit—thus No. 7 temper may refer to 0.65 to 0.75 per cent. carbon, or it may be represented by whatever the individual company has arbitrarily selected. In this connection it should be noted that this “temper” does not refer to, and should not be confused with the word temper as indicating the operation of “letting down” the steel after hardening.

General recommendations for the proper carbon content to use for various tools are given in the following table; these, however, must not be regarded as absolute, for much will depend upon the grade of steel and upon the exact use of the tool.

#### APPROXIMATE CARBON CONTENT FOR ORDINARY TOOLS

Carbon, Per Cent.	Tools
1.50	Tools requiring extreme hardness. For turning chilled-rolls and tempered gun-forgings. Roll corrugating.
1.40	Hard lathe work generally. Chilled-roll turning. Corrugating. Graver tools. Brass-working tools.
1.30	General lathe, slotter and planer tools. Razors. Drawing dies.

Carbon,  
Per Cent.

Tools

- Mandrels, granite points, scale pivots, bush hammers, peen-hammers.  
 Ball-races.  
 Files.  
 Trimming dies. Cutting dies.
- 1.20 Twist drills. Small taps.  
 Screw dies, threading dies.  
 Edge tools generally. Cutlery.  
 Cold stamping dies, leather-cutting dies, cloth dies, glove dies.  
 Nail dies, jewelers' rolls and dies.
- 1.10 Milling cutters and circular cutters of all descriptions.  
 Wood-working tools, forming tools, saws, mill picks, axes.  
 Small punches.  
 Taps.  
 Cup and cone steel.  
 Small springs. Anvils.
- 1.00 Reamers, drifts, broaches.  
 Large milling cutters, saw swages.  
 Springs.  
 Mining drills, channeling drills.  
 Large cutting and trimming dies.
- 0.90 Hand chisels, punches.  
 Drop dies for cold work, small shear knives.  
 Chipping chisels.  
 Cutting and blanking punches and dies.
- 0.80 Large shear knives, chisels, hammers, sledges, track chisels.  
 Cold sets, forging dies, hammer dies, boiler-maker's tools.  
 Vise-jaws. Oil-well bits and jars. Mason's tools.
- 0.70 Smith shop tools, track tools, cupping tools, hot sets.  
 Set screws.
- 0.60 Hot work and battering tools generally. Bolt and rivet headers.  
 Hot drop forging dies. Rivet sets. Flatteners, fullers, wedges.
- 0.50 Machinery parts. Track bolt dies where water is continually running on dies (hot work).

**Navy Specifications.**—The United States Navy specifies the following straight carbon tool steel for its general requirements:

Class.	I.	II.	III.	IV.
Carbon.....	1.25-1.15	1.15-1.05	0.95-0.85	0.85-0.75
Manganese.....	0.35-0.15	0.35-0.15	0.35-0.15	0.35-0.15
Phosphorus.....	0.015-0	0.015-0	0.02-0	0.02-0
Sulphur.....	0.02-0	0.02-0	0.02-0	0.025-0
Silicon.....	0.40-0.10	0.40-0.10	0.40-0.10	0.40-0.10

Chrome and vanadium optional.

Class I. Lathe and planer tools, drills, taps, reamers, screw-cutting dies; taps and tools requiring keen cutting edge combined with great hardness.

Class II. Milling cutters, mandrels, trimmer dies, threading dies, and general machine-shop tools requiring keen cutting edge combined with hardness.

Class III. Pneumatic chisels, punches, shear-blades, etc., and in general tools requiring hard surface with considerable tenacity.

Class IV. Rivet sets, hammers, cupping tools, smith tools, hot-drop forge dies, etc.; tools requiring great toughness combined with necessary hardness.

The Navy Department also maintains the requirements as to grade by requiring a steel which will stand rehardening a specified number of times without cracking.

**General Properties.**—The following table shows the relative toughness and hardness of tool steel of the different carbon contents:

Carbon,  
Per Cent.

0.50 Toughness only.

0.60 Great toughness with properties suitable for hardening and tempering.

0.70 Excellent toughness, but with cutting edge.

0.80 Tough tool steel, withstanding shocks, etc.

0.90 Good cutting edge but with toughness an important factor.

1.00 Toughness and cutting edge about equal.

1.20 Great hardness combined with some toughness.

1.30 Great hardness in cutting edge. Toughness slight factor.

1.40 Extreme hardness in cutting edge first requirement.  
Toughness slight factor.

Some metallurgists consider that it is safer to select a too hard steel and draw the temper at a higher temperature than to choose a too



soft steel with a view to increasing its hardness by a weaker tempering. Opposed to this is the fact that the higher the carbon content the more the care which will be required in the hardening operation, since the steel becomes more sensitive to overheating.

## GENERAL TEMPERING COLORS FOR TOOLS

- Faint yellow: Steel-engraving tools.  
Light turning tools.  
Hammer faces.  
Planing tools for steel.  
Ivory-cutting tools.  
Planing tools for iron.  
Paper-cutting knives.  
Wood-engraving tools.
- Light yellow: Milling and other circular cutters for metal.  
Bone-cutting tools.  
Scrapers for brass.  
Shear blades in general.  
Boring cutters.  
Leather-cutting dies.  
Screw dies.  
Inserted saw teeth.  
Taps.  
Rock drills.  
Chasing tools.  
Penknives.
- Straw: Dies and punches in general.  
Moulding and planing cutters for hardwood.  
Reamers.  
Gouges.  
Brace bits.  
Plane irons.  
Stone-cutting tools.
- Deep straw: Twist drills.  
Cup tools.  
Wood borers.  
Circular saws for cold metal.  
Cooper's tools.  
Augers.

Brown.	Drifts. Circular cutters for wood. Dental and surgical instruments. Axes and adzes. Saws for bone and ivory.
Peacock:	Cold sets for steel and cast iron. Hand chisels for steel and iron. Boiler-maker's tools. Firmer chisels. Hack saws.
Purple.	Moulding and planer cutters for soft wood. Smith tools and battering tools generally.
Blue:	Screwdrivers. Saws for wood. Springs in general.

These colors are for general crucible steel with low manganese. Their applicability to particular work and special steels may be taken

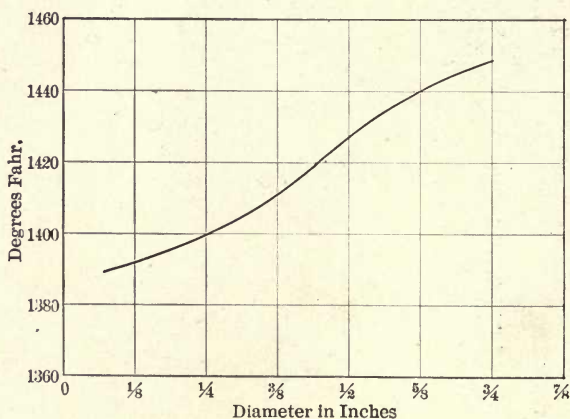


FIG. 199.—Temperature-size Curve for Hardening Tools.

in a general way, but that temperature must be adopted which will suit the special work or steel in hand.

**Hardening.**—We have previously discussed the fact that with any increase in the mass of the steel there is a corresponding decrease in both the maximum surface hardness and the depth of hardness, when quenched from the same temperature. This difference in hardness is due to the difference in the rate of cooling of the small

and large sections. In order to produce the same degree of hardness in a small and large section, as applied to small tools, it is necessary to heat the larger section hotter for hardening than the smaller. To illustrate: Matthews and Stagg have worked out the relation of mass to temperature for one particular grade of the same tool steel in which the sizes varied from  $\frac{1}{16}$  in. diameter to  $\frac{3}{4}$  in. diameter, and

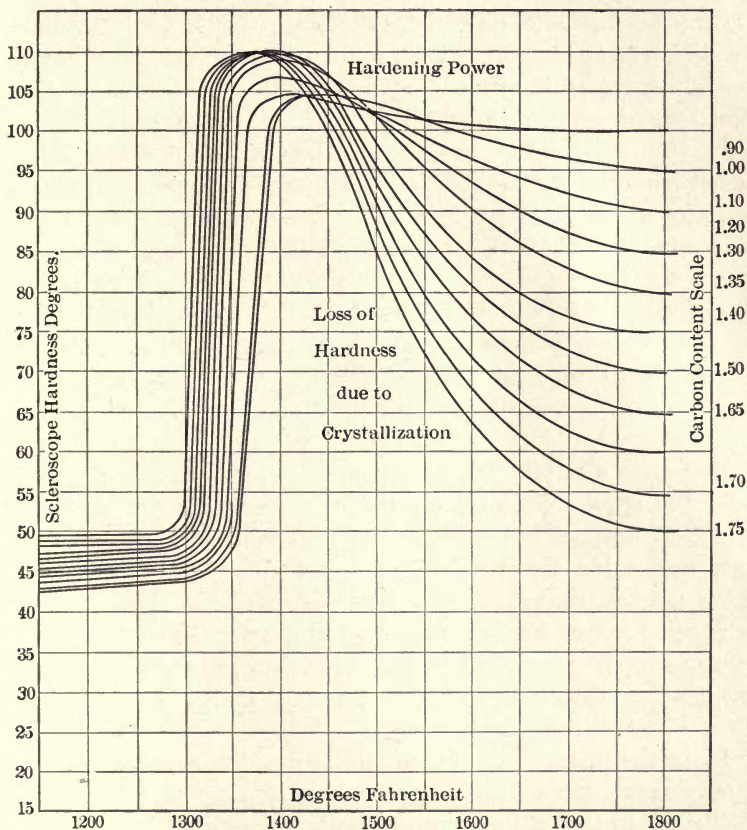


FIG. 200.—Loss of Hardness Due to High Hardening Temperatures. (Shore.)

found that a difference of about 60° F. in heating was necessary to produce the same degree of hardness in the two extreme sizes. Their temperature-size curve is given in Fig. 199.

The table on page 365 gives the approximate temperatures for handling general tool steels. Two columns are given under hardening temperatures as representing the best practice of two well-known



steel companies. As a general proposition, the lowest temperature should be used for hardening which will give the desired results: the use of abnormally high temperatures will increase the grain size, weaken the steel, and reduce the hardness. These last factors become even the more apparent with increase in the carbon content, as is roughly illustrated by the scleroscope readings as given in Shore's chart in Fig. 200.

On the other hand, on account of mass action and other individual and distinctive shop conditions, it is difficult to set the upper limit over which hardening should not be done. Certain classes of work often require temperatures which might prove excessive for other work; thus one instance has come to the author's attention in which the hardening of certain  $1\frac{3}{16}$ -in. rounds of 0.9 per cent. carbon stock are hardened at 1600° to 1620° F. and 80 per cent. more service is being obtained than from the same steel hardened at 1460° F. Again, another well-known company hardens 0.9 per cent. carbon steel of approximately the same size at 1370° F. and obtains better service than when hardened at higher temperatures. Each case, in other words, must be handled separately and those temperatures worked out which will give the best solution of that particular problem.

**Distortion Factors.**—Slender pieces of steel, when hot, will bend under the application of a steady, even though slight, load. The weight of the part being heated for hardening is often sufficient to cause noticeable distortion if the tool is placed in the furnace in such a manner that it is not carefully supported. For this reason, such tools are best heated when held in a vertical position, with the point of support at the upper end of the piece, the tool being so held that it automatically comes to the normal position as will a plumb-bob.

Distortion may be due to the initial condition of the steel, such as may result from forging, rolling, machining, etc. Any strains which exist in the tool previous to heating for hardening are relieved when the piece is heated, but the readjustment of such strains may cause a bending or twisting of the tool. In making the tool it is advisable to rough down to within about  $\frac{1}{16}$  in. of the finished size and then anneal in some non-oxidizing material to relieve the machining strains. If the tools are not straight after annealing, they should be heated, straightened while hot (do not straighten in the cold), and then reannealed. The tools are then finished and are ready for hardening.

Approximate Carbon Content Per Cent.	General Use or "Temper."	Welding Properties.	Approximate Forging Temperatures, Deg. F.	Critical Range, Deg. F.	Approximate Hardening Temperatures, Deg. F.	
					A.	B.
0.60	Hot work tools.....	Welds readily.....	1600-1800	1340-1380	1410-1460	about 1480
0.70	Smith tools.....	Welds readily.....	1600-1700	1340-1375	1400-1450	about 1470
0.80	Shears.....	Weldable.....	1600-1700	1340-1365	1390-1450	about 1465
0.90	Chisels.....	Weldable.....	1600-1650	1340-1360	1375-1450	about 1455
1.00	Reamers.....	Weldable.....	1600	1340-1360	1375-1450	about 1450
1.10	Milling cutters.....	Weldable.....	1550	1340-1360	1375-1430	about 1440
1.20	Drills.....	Requires care.....	1550	1340-1360	1375-1430	about 1425
1.30	General lathe work....	Requires great care and suitable flux....	1500	1340-1360	1375-1425	about 1415
1.40	Hard lathe work.....	Requires extreme care, experience, and flux..	1500	1340-1360	1375-1425	about 1400

The influence of annealing or previous hardening operations upon the change in shape, such as increase or decrease in diameter and length, or combinations of these, is very difficult to foretell. As a general rule, however, such changes are the more marked with repetitive hardenings, and with increased percentages of carbon.

**Changes in Length.**—Most tool steel has a tendency to contract in length upon hardening, and especially after previous annealing or hardenings. This change, whether it is expansion or shrinkage, is dependent upon the chemical composition and uniformity of the steel, the grain size and influence of the mechanical elaboration and annealing, the uniformity and amount of heat used in hardening, the method and rapidity of cooling, and innumerable other variables. The commercial application of heat-treatment principles when applied to fine tools for their standardization to exact measurements must be along the lines of standardizing each step of the process. The steel must initially be kept uniform in composition and physical test; the limits of treatment must be held to a minimum difference; and having somewhat accomplished these aims, the average change of size for specific dimensions must be studied and the tool made accordingly. Thus in the matter of taps, by obtaining the average contraction lengthwise for a given size tap blank, under standard conditions, the thread may be cut upon lathes having the lead screws so adjusted that the pitch given to the tap before hardening will just come right after hardening.

**Changes in Diameter.**—Assuming that the many other variables affecting distortion might be reduced to a constant or standard, it is a generally accepted condition that there is a relationship existing between the amount of distortion by swelling after hardening and the original diameter of the piece. Most slender tools, in ordinary commercial practice, have a tendency to expand in diameter after hardening. In factories where a standard steel and standard methods are in vogue the amount of increase is a very important factor, as is shown by the following data obtained from an exhaustive study<sup>1</sup> of taps:

Thus this particular problem was attacked with the view of obtaining, under standard shop conditions, the average increase in diameter due to hardening for each size of tap. With these results it was then possible to determine the necessary angle diameter of the tap before hardening, so that the hardened tap would meet the final requirements.

<sup>1</sup> Woodward.



Diameter of Tap.	Average Increase in Diameter.	Diameter of Tap.	Average Increase in Diameter.
$\frac{1}{16}$ inch	.....	$1\frac{1}{2}$ inch	0.0025
$\frac{1}{8}$	0.00025	$1\frac{3}{4}$	0.0025
$\frac{1}{4}$	0.0005	2	0.003
$\frac{1}{2}$	0.001	$2\frac{1}{2}$	0.003
$\frac{3}{4}$	0.0015	3	0.0035
1	0.002	$3\frac{1}{2}$	0.0035
$1\frac{1}{4}$	0.002	4	0.004

It was also found, however, that experiments upon the same steel, under apparently the same conditions, showed that there may be very great variations in the effect of hardening upon the diameter; and when the various other factors are taken into account, the difficulty of prognosticating exactly what is going to happen is even more apparent.

**Heating.**—Much of the difficulty experienced through distortion or cracking may be largely diminished by the proper application of the principles of heating such as have been discussed elsewhere. The heating should be done slowly, carefully and at a uniform rate. In no case should the temperature of the furnace be greater than the maximum temperature to which the steel is to be heated. After the steel has been thoroughly heated, a further continuance will only tend to weaken the steel by increasing the grain size. The furnace should be of such design, construction and operation that it shall be of uniform temperature over its whole hearth, shall heat at a uniform rate, shall not be greatly affected by the introduction of fresh charges, shall have a neutral or reducing atmosphere, and shall be under exact control. Further, it is not only the temperature to which the steel has been heated in the furnace that counts, but also the temperature (and uniformity of temperature) of the steel when it goes into the quenching bath.

#### HEAT TREATMENT OF TOOLS

In the following pages there is given a description of practical methods of treating certain tools. It is not intended that the data shall be comprehensive of all methods or of all tools, but shall give practical hints and methods which may aid the man in the *small* shop who may have such work to do but occasionally. It should also be remembered that the ideas given are representative of a

*type* of treatment or tool, and which may find application for many uses not given. The methods given are taken from practical work, and have given satisfaction.

**Chisels.**—Chisels belong to that class of tools which can be advantageously hardened without first grinding away the “skin.” Chisels are not hardened by heating up the whole tool, but only applying the heat to 2 ins. or so of the cutting end; too short a distance is detrimental, as the long, unhardened shank may bend under heavy blows. In quenching, care should be used to avoid a distinct line of demarkation between the hardened and unhardened parts, as otherwise the end may break off in service. After hardening the cutting end by immersing in water and at the same time moving the chisel up and down, the tool should be removed while sufficient heat for tempering still remains in the shank. The cutting edge is brightened with emery cloth. Temper colors will soon appear in the brightened spot, which are caused by the heat from the shank “running down” towards the cutting edge; the temper colors may be “spread out” by holding the end near the fire if it is desired to have a broad band near the edge. When the proper temper color is obtained at and near the edge, the chisel should be immediately plunged into water until cold in order to prevent further softening.

The degree of tempering depends upon the steel which has been used, the duties in service and upon the general experience and judgment of the hardener. In general it may be said that chisels for metal should be tempered to about a peacock color; for stone to a purple color, although many stone and granite chisels are drawn to only a light straw color; and for soft material to a blue color. If a very tough steel is desired, the chisels may be given a double tempering by heating to the temper color twice, the first color being rubbed off after quenching. The lower the carbon used the lower should be the tempering; in fact, a 0.45 per cent. carbon steel is sometimes used after hardening without subsequent tempering.

An excellent plan in treating chisels is to oil treat the blank before forging out, quenching the steel in oil and from a temperature sufficient to harden it well. This will stiffen the shank and keep the head from upsetting during use.

The problem of producing a good chipping chisel is simple, and yet has met with more difficulties than the majority of other such tools. The correct adjustment of temperatures plays a most important part in this work. For forging, the steel should be heated

up gradually and not much beyond a bright-red heat.<sup>1</sup> The work should be done rapidly, aiming to obtain the greatest reduction to size while the steel is yet near its first heat; as the temperature falls, the blows should be lighter and quicker. It has been the author's experience that added toughness is given to the steel if these light, quick blows are carried on until the steel nears a dull-red heat. If reheating is necessary, adopt the same care in raising the temperature as before. The chisel should be immediately hardened and tempered after forging when possible. If the pressure of work will not permit of this, the chisel should be allowed to cool as slowly as possible by sticking the hot end in *dry* dirt; this latter will tend to eliminate the cooling strains which might otherwise be set up. For hardening heat slowly to the lowest temperature at which the steel will harden (generally about 1350° to 1400° F.), allow the heat to penetrate and harden as usual. If care is used, and sufficient thought has been given to the design of the chisel, a hundred per cent. improvement may be easily obtained over the ordinary "hit or miss" method.

An open-hearth steel which has given unusual service for pneumatic chipping chisels is as follows: Carbon, 0.90 to 1.00 per cent.; manganese .50; phosphorus and sulphur low; chrome, 0.50 per cent. The hardening temperature of this steel is about 1400° F.

**Die Blocks.**—The problem of satisfactorily treating die blocks is one which will try the hardener's knowledge and patience, increasing in difficulty with the intricacy of design and size. Primarily the requirements of any die are (1) a hard face, (2) sufficient depth of hardening to prevent the impression from sinking, and (3) a tough back or body to take up the shock or blow. Further, the hardening must be conducted in such a manner as will prevent any change of size—such as warping—besides producing a clean, sharp impression free from scale, pitting or checks. These fundamental requirements, assuming that the right kind of steel is used, involve the factors of proper heating and the most suitable method of cooling.

<sup>1</sup> For the convenience of the tool hardener who has to work without a pyrometer and must gauge temperatures by the eye, the following table of approximate heat colors in moderate diffused daylight is given:

White.....	2200° F.	Cherry or full red.....	1375° F.
Light yellow.....	1975	Medium cherry.....	1250
Lemon.....	1825	Dark cherry.....	1175
Orange.....	1725	Blood red.....	1050
Salmon.....	1650	Faint red.....	900
Bright red.....	1550		



More die blocks are warped or cracked through improper heating than through any other cause. It is absolutely essential that the entire mass of the steel of the block shall be heated *carefully, uniformly, through and through*, to the *proper temperature*.

It is always best to allow the die to heat up with the furnace so that any strains which may exist in the steel may be removed gradually and give the mass of steel ample time to adjust itself to the rise in temperature. If the furnace for heating for hardening is already at or near the quenching temperature when the die is ready for heating, it will be advisable carefully to preheat the die in a separate furnace. Equipment is subsequently described for automatically preheating and full-heating in the same furnace. In no case should the temperature of the heating furnace be greater than the maximum temperature from which the steel is to be quenched. The practice—unfortunately common—of forcing the furnace in order more quickly to heat the steel is to be strongly condemned; such practice must inevitably result in the overheating of the edges or corners of the die and produce unsatisfactory results. The extra time spent in careful and uniform preheating, and in all subsequent heating operations, will be well worth the expense.

The exact temperature best suited for hardening may be mentioned here only in a general way. The chemical composition of the steel, the size of the die block, the depth of hardness required, the condition of the steel before hardening, and many other factors must be taken into consideration. In general, nickel and chrome nickel steels may be quenched at lower temperatures than those used for the corresponding carbon steels, while vanadium and chrome vanadium steels usually require higher temperatures. Again, the greater the mass of the steel, and the greater the depth of hardness required, the higher is the temperature for quenching. Some die hardeners even find that a temperature which will produce a slightly coarse grain is advisable for certain classes of work, such as dies for cold forming under a heavy drop. In other words, the proper temperature for hardening must be determined by experiment, but the lowest temperature which will produce the desired results is always the best.

The next, and a vastly important factor, is the duration of heating at the predetermined temperature for hardening. The point to be emphasized is that the mass of the steel must be uniformly heated throughout—and this takes time. Not only must the outer sections attain the necessary degree of heat, but also the very

center of the die. Disregard of this fundamental principle is the basis of a large proportion of the failures through cracking or warping, and which are so often attributed to "the steel is no good." If the die block lays directly on the hearth of the furnace (and this, it might be mentioned, is not the best practice, since any work is best heated when the hot gas currents can circulate entirely around it), the penetration of the heat may be roughly determined by moving the block to one side and noting the color of the space vacated; if this area is not of the same color as the rest of the furnace floor the heat has not thoroughly penetrated to the center of the die. This test, called the "drawrouagh" by old English hardeners, should be followed even though the play of heat colors over the exposed portions of the block appear uniform.

For protection of the impression from oxidation through contact with the air, the faces of the dies may be packed in carbonaceous material. One of the large manufacturers of silverware packs his dies as follows: A small sheet-iron pan, about 2 ins. high and about an inch or so wider than the die all around, is partly filled with granulated animal charcoal or bone. The die is then pressed firmly upon the charcoal, forming an impression, and is then carefully removed. This impression is sprinkled with powdered animal charcoal, and with very fine steel filings. The die is carefully replaced in position, surrounded with more granulated animal charcoal to the height of the pan, and the space between the top of the pan and the die carefully luted with fire-clay. Upon heating, the filings and powdered charcoal fuse together upon the surface of the steel, forming a protective coating which eliminates oxidation during heating, but which is washed off during the quenching. A little brushing with oil and emery powder will immediately produce a clean, bright surface. Another method is first to paint the surface of the die with a thick paste made of linseed or cottonseed oil and powdered bone-black; the die is then placed in a shallow pan upon a half-and-half mixture of fresh bone and powdered charcoal, in a suitable pan or box, which is then filled and luted as above.

The old-time method of an immediate and total quenching of the block until it is quite cold should be attempted only with the simplest forms and small sizes of dies. Large blocks have a great tendency to warp, bulge, or even crack if a total immersion is adopted, this being caused by the unequal contraction of the metal of the surface and of the core. It may be said, however, that this difficulty may be largely avoided if the block is previously given a special



treatment consisting of oil quenching from just over the critical range, followed by an annealing at a temperature just under the lower critical range. Total quenching also should not be used if an extremely hard face is desired, since the heat cannot usually be removed quickly enough.

The best practice for hardening large die blocks consists in first carefully preheating the die, then slowly raising it to the hardening temperature and allowing it to soak at this temperature until it is thoroughly heated. For this work a furnace should be used in which accurate temperatures and uniform heating can be obtained. Large blocks may be most easily handled by the use of a hoist on a swinging run-way, mono-rail or overhead crane, and equipped with tongs or "dogs." The dogs fit into holes which have previously been drilled in opposite sides of the block about half way between the upper and lower faces.

When the block is properly heated, it is removed to the front of the furnace, gripped with the dogs, run over to a position above the quenching tank, lowered face-downwards entirely into the water or oil for a few seconds (to prevent warping), and then raised out of the quenching bath until immersed about 1 in. deeper than the depth of the deepest impression in the die. The surface of the bath should be kept in motion, or else the block should be slowly raised and lowered a little so that there will be no one line of hardening. The hardening will be greatly increased if a stream or heavy spray of water (assuming water to be used for hardening) is directed against the face of the block, or into the impression. In the case of blocks which contain a deep impression, such as are used for certain classes of gears, etc., it will be necessary to have a stream of water thus impinge upon the impression in order to harden it; the face of the block will take on great hardness, and the heat from the unsubmerged part will gradually be drawn out.

When the face of the block is entirely cold, and the majority of the heat taken out of the other portion of the block (usually at about a very dark red, but dependent upon the size of the block), it is raised out of the water, reversed to face up, and brightened with emery paper. The heat in the hot part of the block will gradually temper the hardened face. When this approaches a good straw color the block is immersed in water or oil until cold; in some instances where a softer block is desired, the block may be allowed to cool in the open without the use of water to stop the temper. In case there is not sufficient heat left in the block after hardening to bring out



the desired temper color, the block may be stood in front of the furnace, back to the heat, or placed on a hot bar of steel, or laid on top of a low smith fire, until the proper temper is reached. Die blocks will generally give more uniform service when drawn in a tempering bath when such is possible. In case the block is of intricate design and requires very particular tempering in weak spots, this may be done by the local application of heat by means of hot plates, etc.

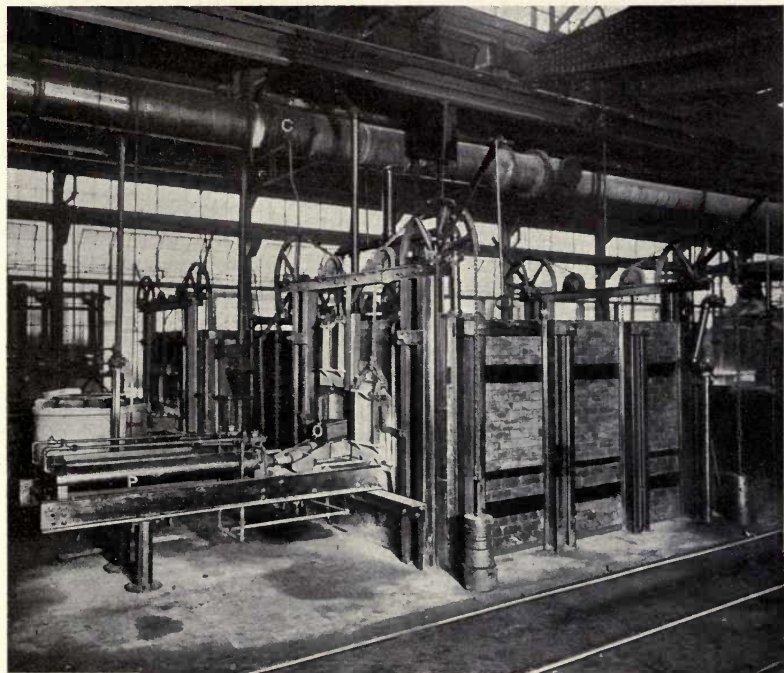


FIG. 201.—Intake End of Special Furnace for Hardening Forging Dies.  
("Machinery.")

Die blocks hardened and tempered as directed above should produce a strong, tough base and core, increasing in hardness as the face is approached.

Semi-automatic furnaces for heating die blocks for hardening, in which the preheating as well as the final heating are done in the same furnace, are illustrated in Figs. 201 and 202. Four runways, filled with 3-in. malleable-iron balls, extend throughout the length of the heating floor of the furnace. Castings which fit over the

balls in two of these run-ways and which are of suitable size to carry one of the dies, are placed in position in the end of the furnace shown in Fig. 201. When the cold die is placed on this casting, as shown at *O*, one of the pneumatic pushers *P* is brought into play and the castings act as a cart, carrying the die into the furnace. By following the first casting and its die with others, the furnace is gradually filled, the ram pushing the whole line of dies further into the furnace with each new addition. The furnace is so designed and operated that the temperature at the charging end is low, but gradually

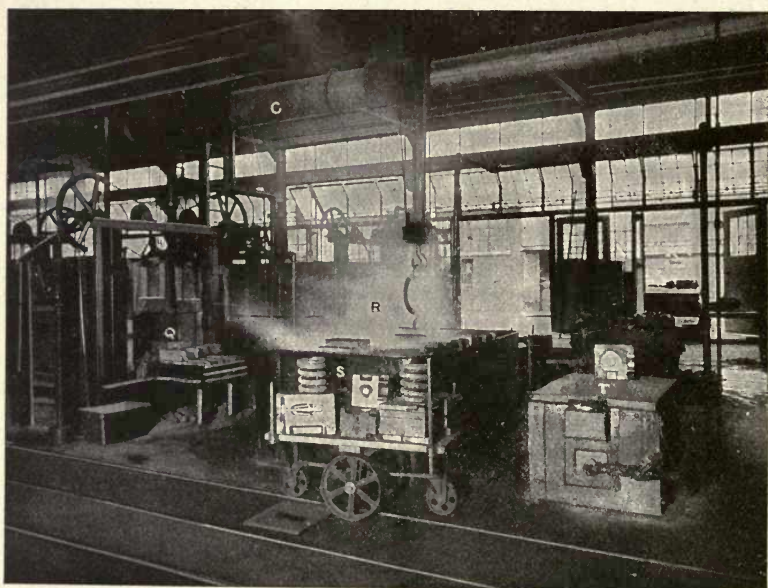


FIG. 202.—Quenching and Tempering Dies. ("Machinery.")

increases up to the maximum near the other end of the furnace; preheating and the final heating are thus obtained in the same furnace. Each furnace is double tracked and heats two rows of dies at once. At the end of the furnace shown in Fig. 202 the hot dies come out on the extension of the run-way marked *Q*. The faces of the dies are turned downwards so that the dies may be picked up by the traveling crane and lowered into the quenching tank, as shown at *R*. A stream of water also plays against the impression, as usual. The hot plate shown at *T* is used for the tempering.

Engraved dies for spoons, forks, knives, etc., are treated at one plant by the following method. After packing and heating as described in a previous section, the dies are quenched face up in water at a temperature of about 70° to 80° F., to a depth of within about  $\frac{1}{2}$  in. of the face. Water at this temperature seems to give the best results in this particular instance—colder water is too harsh, while warmer water does not sufficiently distribute the strains nor give sufficient hardness. As soon as the cooling effect just begins to creep towards the face of the die, and which only takes a few

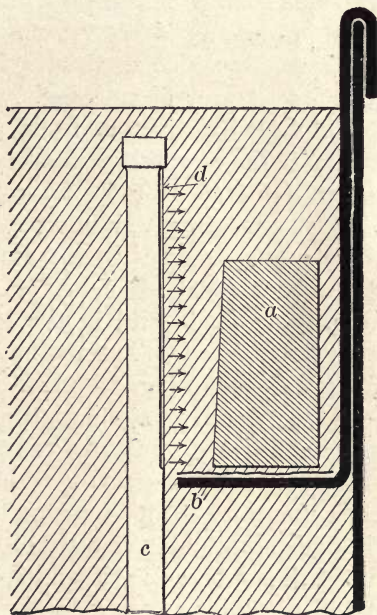


FIG. 203.—Method of Hardening Engraved Die.

seconds, the die is immediately wholly immersed in a vertical position in the water, with the impression turned toward a heavy stream of water which impinges directly upon it. The arrangement of the quenching bath is shown in Fig. 203: the die (*a*) rests upon a wire platform (*b*); the water is supplied under pressure through a  $1\frac{1}{2}$ -in. pipe (*c*), flowing out through a  $\frac{1}{4}$ -in. slot (*d*) which extends from the level of the die support to the top of the pipe. The die remains in the water bath until the “singing” has stopped, about 50 to 90 seconds, and is then cooled in oil until cold. The hardened die is later tempered in oil to 435° F.



Many alloy steels have been experimented with in recent years for the purpose of increasing the production of forgings from a given impression, thus avoiding the loss of time and expense incurred in redressing the die-blocks. A chrome nickel steel containing about 0.50 to 0.60 per cent. carbon, 0.50 per cent. chrome and 1.50 per cent. nickel has been found to give most economical results. These die blocks are hardened and tempered in the usual way, using a temperature of 1400° for the hardening heat. If the carbon content runs above 0.60 or 0.65 per cent. it has been the author's experience that cracking during or directly after hardening may result. These blocks are greatly improved, not only in the length of service to be obtained, but also in the elimination of warpage during hardening, and of danger of cracking, by giving the block, before machining, a full heat treatment and toughening or annealing; blocks which approximate the composition noted should be quenched in oil from a temperature of 1400° to 1450° F., and then full annealed at about 1250° F. Such a treatment gives excellent results, and will also show up any defects such as pipes, seams, etc., before the expensive machine work has been done.

Dies used in engraving work, and in the jewelry and optical trades, must have a glass finish, both in smoothness and in hardness. If subjected to the usual quenching, followed by sand-blast, acid bath or cyanide, a large amount of stoning and polishing would be required. This may be obviated by the use of borax or boracic acid in the following manner. Fill the matrix with powdered boracic acid and place near a fire until it melts, which temperature is considerably below the tempering point or color of the steel. Follow this with a second addition of boracic acid and then harden as usual. Although the salt will generally come off in the quenching, it protects the polished surface of the die and does not interfere with the hardening. In case the salt does not come off in quenching, it may be easily removed by live steam or boiling water. The hardening may be done by complete or partial submersion, depending upon the thickness and general design of the die. Engraving dies are usually tempered to a light straw color.

**Drills.**—For occasional work in hardening drills, the following procedure may be used: If an open fire is the only available source of heat for hardening, the points of the drill should be kept out of the hottest part of the fire at first, drawing them in as the upper parts become heated. The heat should extend over a considerable portion of the drill. Quench vertically in water, and keep the drill

moving up and down so that there is no abrupt line of demarkation of the hardening. If the drill is held quietly in the water, fracture across the water line is a common occurrence when the drill is placed in service. Allow the drill to remain in the water until the immersed part is entirely cold. Remove, brighten, and allow the heat in the shank to run into the hardened part until a dark straw color appears on the cutting edge. The drill should then be immediately and entirely immersed in water. If there is not sufficient heat in the shank to bring out the temper color, use hot ashes, or similar means. The drawing operation upon hardened drills should preferably be carried out in an oil or salt bath subsequent to straightening; drawing expensive tools to color is poor practice.

It is always advisable, however, if an open fire must be used for heating, as noted above, to heat the drill in a pipe or tube to prevent the direct contact of the fire and the steel, or with charcoal to prevent oxidation. The heating should be done slowly, uniformly, and to as low a temperature as is possible and consistent with the desired results.

In cases where a large number of drills are to be hardened, it is advisable to use a special hardening tank. The shape of the lands of the drill is such that the steam formed by the contact of the water and the hot metal will in many instances prevent the water from penetrating to the flutes and properly hardening them, besides having a similar influence on the end of the drill, which will become the new cutting edge as the point is ground back. This buffer or blanket of steam may be eliminated by maintaining a constant flow of cold water into the grooves and against the end of the drills. Perforated pipes may be placed up the sides of the quenching tank, and through which the cold water is forced into the grooves; similarly, a jet from the bottom strikes against the end of the drill.

For drills for holes under  $\frac{1}{4}$  in. in diameter, the hardening heat should be allowed to penetrate only through the cutting part. The drill should then be quenched entirely and the temper drawn to suit the work. The reason for not allowing the hardening heat thoroughly to penetrate to the core of the drill is that sudden quenching of a small, slender piece might cause severe strains to be set up in the steel; such drills also require a tough core to be able to withstand the torsional effect in the actual drilling operation. Most of the small drills are quenched in oil. The temper color is usually a dark straw. If the tempering is accomplished by placing the drills upon a heated



bar, the cutting parts must be allowed to project for some distance over the edge of the hot bar, for otherwise the heat will be too suddenly applied.

**Milling Cutters.**—Under this class are included cutters of varying description, such as milling cutters, forming cutters, slotting cutters, angle cutters, etc. This consists, in general, of a cylindrical piece of steel with a bore through the center, and teeth on the circumference, sides, or both. The unequal forces of contraction and expansion affect these tools to a large extent. In designing a cutter, as large a mandrel hole as is possible should be used, as larger holes will permit the steel to be hardened more uniformly. If the mandrel holes are standardized, large cutters may have a part of the sides (in the absence of side or angular teeth) dished or paneled out at the place which would tend to harden last, that is, half way between the two circumferences.

Great care should be used in heating milling cutters for hardening. The heating atmosphere should be neutral or slightly reducing to protect the teeth. If an open fire is used, the fuel should not be allowed to come in contact with the cutter: this may be done by resting the cutter on a fire-brick or plate. If a hearth furnace is used, the cutter should not touch the floor or walls of the furnace, but should be supported by fire-bricks or other suitable methods. If tongs are used in handling, care must be used so that the tongs do not touch the cutting edges; the use of wires is better practice. If the cutter is supported on bricks, or laid on plates, it must be turned repeatedly in heating so as not to leave any unevenly heated spots. The cutter may be conveniently held in the quenching bath by using a small round bar which has three prongs welded to one end, and which extend at right angles to the axis of the bar, by slipping the other end of the bar through the mandrel hole of the cutter; the latter will rest on the prongs, and then can be conveniently lowered into the quenching bath.

Ordinary cutters are best hardened by the use of two small circular plates of a diameter slightly greater than that of the cutter, and with holes bored through the center corresponding to the size of the mandrel hole of the cutter. One plate is placed on each end of the cutter, and the whole placed on the suspension tool as described above and immersed vertically in the quenching bath. By the use of these plates, the hardening will affect the steel along the entire length of the teeth and at right angles to the center line of the cutter. This will also eliminate the circular fracture or



flaking of the teeth which so often characterizes milling cutters subjected to uneven cooling. While in the quenching bath, the cutter should be moved up and down and not from side to side; this will permit the solution to pass through the center hole and give an evenly hardened core. The combined use of water and oil ("broken hardening") in the following manner is good for hardening for large cutters: quench in water until the "singing" caused by the water boiling on the hot steel has stopped, and then immerse in oil until cold; warm the cutter in boiling water to relieve the strains and temper when convenient. Pack-hardening is also used to some extent for milling cutters in order to prevent oxidation; in this case each piece should be quenched separately. Salt baths and lead baths are also used for heating. One of the main points to be observed in quenching milling cutters is that long cutters should be plunged vertically and thin ones edgewise.

The tempering of milling cutters is often done by the insertion of a hot rod through the mandrel hole and revolving the cutter on it until the proper temper color is obtained. The most satisfactory results are to be obtained with the use of an oil bath, as an even hardness can be best obtained in this manner. Small cutters are tempered to a light straw color, or yellowish-white. For medium-sized cutters a good straw color may be used. Very large cutters, on account of the lesser effect of the hardening, may not require tempering, but it is always advisable to heat them in boiling water to make them uniform and remove the hardening strains.

For hollow mills it is not necessary to heat for hardening very much above the teeth, as it is not required that the back should be hard. Harden with the teeth upwards, working the piece up and down in the quenching bath to get the solution circulating through the hole.

T-slot milling cutters should be hardened, not only through the cutting portion, but also through the entire length of the neck, especially if this is of small diameter. In tempering, the cutting portion should be drawn to a straw color and the neck to a blue color.

**Files.**—Before the file blanks can be ground and the teeth cut it is necessary to anneal the steel. This is often accomplished by packing the blanks in air-tight oblong boxes and annealing at about 1300° to 1400° F.

Lead baths continue to be most used as the heating medium. Salt baths have been tried with varying degrees of success, but in the main have proven unsatisfactory. This is due in a large measure

to the fact that oxide of iron (scale) may settle upon the teeth of the file, causing soft spots when hardened. The method of dipping the file into a solution of ferrocyanide and allowing the coating to dry upon the surface of the steel before heating has been tried. The objections to the use of this method are that a decomposition of the ferrocyanide will yield additional iron oxide and poisonous fumes. Other salts of a harmless character have been tried with little success. The general procedure is to cover the file with a paste which protects the edges of the teeth in the hardening process, heating in lead to the proper temperature (about 1400° F.) and quenching in water in a vertical position. One file-maker uses a paste made of the following base: ground charred leather, 2 parts; table salt, 4 parts; and flour, 3 parts. The file is given a coat of this paste, which is allowed to dry before heating. It is said that the melting-point of this paste will give the proper hardening temperature. After being hardened, and while the file is still warm, it is put through the final straightening process.

Half-round files require particular attention on account of their tendency to warp: before hardening, the file is bent back on a fixed template of such form as experience has shown will bring the file to a true line upon hardening; the file is placed again in the template before it is quite hard, strained to the proper degree, and water is thrown on the upper surface of the file to make it quite cold before the strain is relieved; the file is then entirely quenched and will usually return "to the true" after the final hardening.

After the final straightening the files are "scrubbed" to remove the paste, and are then washed in lime water and dried by holding them in steam. The tang is then toughened or "blued" by dipping it into a special bath maintained at the proper temperature.

File steel will vary in carbon from 0.90 to 1.60 per cent., according to the size, shape and use of the file; manganese under 0.40 per cent.; low phosphorus and sulphur; and in the case of exceptionally good files, a small percentage of chrome. Nickel is generally considered as detrimental to files.

Reichhelm<sup>1</sup> shows the detrimental effect of heat variations in hardening in the microscopic photographs of two fractures of the same file magnified 160 times. This file is one of the highest grade produced in Europe, and Fig. 204 shows the fracture of this file as imported, while Fig. 205 shows a fracture of the same file, a section of which was rehardened, after the exact degree of heat required

<sup>1</sup> "Machinery," Dec., 1914.



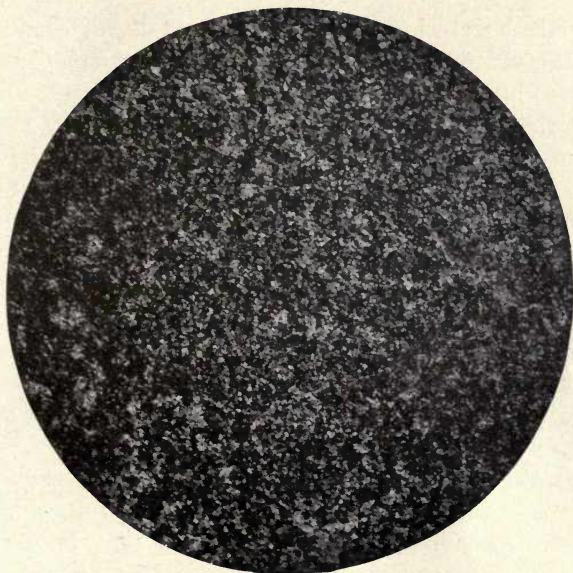


FIG. 204.—Photomicrograph of High-grade Foreign File.  $\times 160$ .  
(Reichhelm.)

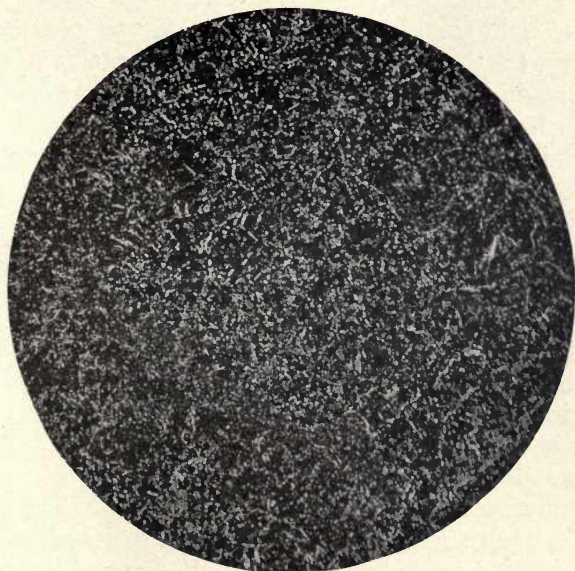


FIG. 205.—Photomicrograph of Same File Rehardened.  $\times 160$ .  
(Reichhelm.)



for this particular steel had been experimentally determined. Fig. 204 therefore shows the result of the best hardening practice in Europe, aided by the pyrometer, while Fig. 205 shows the hardening of this identical file by the correct heat automatically maintained. That any number of files, or tools of any kind, can be hardened so as to show uniformly the excellent fracture exhibited in Fig. 204 is due to automatic heat control, as has been demonstrated conclusively in daily practice for over three years.

Both of the photographs of fractures have been pronounced excellent by competent judges, but the decidedly finer grain and more even diffusion of the carbon shown in Fig. 205 produced a difference in the durability of the file teeth of nearly 50 per cent., as compared with the section of the file as originally hardened and shown in Fig. 204.

**Punches and Dies.**—Similar to all round tools, punches show a great tendency to flake off at the corners, sometimes a whole ring breaking off. Assuming proper heating, this may be overcome to a large extent by means of a water spray. Dies of intricate shape and possessing sharp angles should be most carefully handled. It is often advisable to fill these angles with a little putty or fire-clay to lessen the hardening effect and prevent the formation of quenching strains at right angles to the diagonal. A piece of binding wire may also serve for this purpose. Dies should generally be quenched flat, depending upon the shape of the piece. Small punches should not be quenched in real cold water on account of the liability to cracking under sudden cooling—an oil bath or lukewarm water is far preferable. Dies or any press tools having holes near the edge should always have these holes filled with clay in order to prevent cracking or too great hardening; graphite or asbestos may also be used for plugging the holes for stripper or guide screws. Punches and dies are generally tempered to about a straw color, the depth of this varying according to the thickness and hardness of the material to be punched. The tempering may be carried out by setting the hardened pieces in front of a hot furnace, laying on hot plates, in oil baths or in hot sand.

**Reamers.**—Reamers may be heated in lead to protect the cutting edge from the direct action of the heat and oxygen. The lead may be prevented from sticking to the tool if the latter is brushed, in the case of small reamers, with a little soft soap. Larger reamers may be protected with a paste made of black lead and water or lampblack and linseed oil, both of which should be allowed to dry

on the tool before heating for hardening. If the reamer has been hardened by the use of water alone, and is larger than  $\frac{3}{4}$  in. in diameter, it is advisable to hold it over the fire directly after being removed from the hardening bath, or to set it in hot water for a few moments, in order to remove—as far as possible—the strains which have been caused by the hardening process. This should always be done in the case of shell reamers and other special reamers of any considerable size, whether the quenching medium has been oil or water. Broken hardening is most excellent for tools of this description. Large fluted reamers require to have only the ribs heated to the proper temperature, and then quenched; tempering will not then be required. Ordinary fluted reamers are tempered to a yellowish white or very light straw color. Six-sided or eight-sided reamers may be tempered to a light straw color. Square reamers, triangular reamers and half-round reamers may be tempered to a dark straw color, due to the fact that they take hold of the work more deeply and might break if not tempered a trifle softer.

Half-round reamers should not be quenched vertically, but with the half-round side at an angle of 20 to 45 degrees to the surface of the bath. If half-round reamers should be quenched vertically, it will be necessary to move them in a horizontal manner in the direction of the half-round side at the same time as immersed vertically.

The shanks of reamers, taps, drills, broaches and similar tools may be toughened by local lead tempering.

**Rings.**—Rings, collars and hollow tools comprise a class which require great hardness in the inner circumference or bore. Quenching is usually done by means of allowing a full stream of water to flow through the bore if it is quite small, or in the case of tools with larger bores the insertion of a small pipe with a series of holes in its circumference and through which a continuous stream of water may be forced, forming a spray. In the first case it is advisable to set the tool upon an asbestos-covered washer in which has been cut a hole slightly larger than the size of the bore of the tool and then apply the flange end of the water-supply line or pipe to the other opening. Rings or collars requiring resistance to frictional wear require no tempering. Eccentric rings cannot be quenched as usual, as the relative thickness and thinness of the opposite sides would tend to give unequal expansion and contraction and cause the hole to become oval-shaped. This may be overcome by binding a small

piece of iron or steel to the thin side, heating, and quenching vertically.

**Rivet Sets.**—Rivet sets should never be quenched directly by immersion, as this will tend to make the edges of the cup break off, the center to remain soft, and leave a line of great weakness between



FIG. 206.—Rough Method of Hardening a Rivet Set.

the hardened and unhardened parts. A simple and proper method is to hold the cup under or over a stream of water so that the latter will impinge directly upon the bottom of the cup, as shown in Fig. 206. If there are numbers of rivet sets to be hardened, an arrangement of clips or holders under each tap or spigot may easily be set up. The tempering may be carried out as in the case of chisels (permitting the heat in the shank to temper the cup) or the shank



may be placed in a lead bath and the color allowed to run up into the cup; the rivet set should then be entirely quenched to prevent further softening.

Brearley makes the following points, which are of great interest. Rivet sets may have a short life due to the wear on the head, which is as often a failure as that produced by actual fracture. This is pronounced in the case of annealed stock. He advises hardening the head in oil before hardening the cup. Upon reheating for hardening the cup, and tempering, a steel of great toughness is obtained, which neither splits nor forms a mushroom head.

**Saws.**—Saws may be hardened by either of two methods—direct immersion, or press or roll hardening. Circular saws may be heated by enclosing in a sheet-iron case or box between layers of charcoal. Sufficient space for expansion must be allowed to eliminate chance for buckling. Saws may also be heated on the hearth (if level) of any type of hardening furnace; it is advisable, however, to rest the saw on an iron or steel plate so that the heating may be gradual and uniform. The greater part of the secret for the successful hardening of saws without buckling is a slow and careful heating. The saws when heated to the proper temperature may be taken out separately with tongs or a J-shaped hook. For direct quenching they should be immersed edgewise and in a perfectly vertical position. It is better to have a thin layer of oil on the surface of the water bath, as the oil will ignite when the hot saw enters it, forming a thin, protective coating on the saw and thus lessening the risk of fracture. Oil alone, or oil with tallow dissolved in it will give sufficient hardness for thin saws. The saws may also be placed between lumps of tallow. The latter (tallow) is a better hardener than oil, and therefore gives a greater and deeper hardening. Thin circular saws, and all ordinary saws such as hack saws, hand saws, etc., may be most satisfactorily hardened by means of a press. A common and inexpensive method is to have two cast-iron plates hinged together, with the inner surfaces well oiled with a heavy oil. The hot saw is placed between the plates, which are then clamped together and held until the saw is cold. Thin band saws are often hardened by means of rolls. Circular saws for metal cutting should be tempered to a dark purple color, or to a light blue for wood cutting. Hack saws require tempering to a light purple color.

## CHAPTER XVII

### MISCELLANEOUS TREATMENTS

THE following examples and discussions of certain heat-treatment methods have been selected in an arbitrary manner as representative of distinct classes of work. Many others might just as well have been taken, but the author feels that those selected will perhaps illustrate in a general way some of the many problems which arise in the course of ordinary heat-treatment work.

#### GEARS

**Gear-steel Classification.**—Automobile and similar machine gears may be broadly grouped according to the method of heat treatment, which, of course, is dependent upon the composition of the steel. Thus the three classes are:

(1) The case-hardened gear, using a steel of low-carbon content—generally less than 0.25 per cent—and depending upon the case-carburizing process to give an outer layer of high-carbon steel and upon the subsequent hardening processes to produce the necessary wearing surface of sufficient hardness.

(2) The oil-hardened and tempered gear, using a steel of the alloy type of about 0.45 to 0.55 per cent. carbon.

(3) The hardened gear (without subsequent tempering), using a steel of an intermediary carbon content—about 0.30 per cent.

**Requirements of Gears.**—All high-duty gears require that the steel shall be readily forgeable and machineable, and that after treatment it shall have the greatest possible hardness with the least possible brittleness. In this connection it may be said that surface hardness is often more desirable than tensile strength, while the question of brittleness is very important on account of shocks.

**Case-hardened vs. Oil-tempered Gears.**—The merits or demerits of each type depend largely upon the point of view and the personal experience of the user. Expert opinion may differ widely,

as is shown by the following excerpts from addresses by two well-known metallurgists. One says:<sup>1</sup>

"Several years of observation and contact with the trade leads me to prefer the case-hardened gear. The result of direct tests upon thousands of gears of both types leads me to the following conclusions: (1) The static strength of a case-hardened gear is equal to that of an oil-hardened gear, assuming in both cases that steel of the same class and approximate analysis has been used and that the respective heat treatments have been equally well and properly conducted. (2) Direct experiments proved that the case-hardened gear resists shock better than the oil tempered. (3) As regards resistance to wear the same type is incomparably better, although perhaps not as silent in action.

"One of the leading makers of gears has proved this to his own satisfaction of late by an arrangement of shafts and gears whereby energy is transmitted through two case-hardened gears, in mesh with each other, to two oil-hardened gears. The gears are of the same size. The conditions of the test were severe. Five sets of the oil-hardened gears have already been worn out, while the original case-hardened gears are still in service and show the tools marks.

"Upon the part of many there is a strong objection to case hardening. In nine cases out of ten this is doubtless due to the fact that the case-hardening operation has not been reduced to a science. The depth of case, the relation of case to core, the time and temperature to produce certain results and the exact control of these conditions, together with an accurate knowledge of the material to be treated, are factors that enter into successful case-hardening practice. Further points in favor of this method are easier machining of the blanks, and at least equal static and dynamic properties with less chance of injury in hardening."

Then here is the opposing argument:<sup>2</sup> "For machine tools, hardened high-carbon alloy steel gears appear to be preferable to case-hardened gears for a number of reasons:

"1. Physically they are stronger and tougher and should therefore be better able to resist sudden impacts and extraordinary loads. They do not show by file and scleroscope test the same

<sup>1</sup> J. A. Matthews, "Alloy Steels for Motor Car Construction," Journ. Franklin Inst., May, 1909.

<sup>2</sup> From a paper by J. H. Parker, before National Machine Tool Builders' Assoc.



degree of hardness as case-hardened gears, but, nevertheless, with proper design, the dense-grained gear-tooth resists wear more satisfactorily, as was demonstrated recently by the examination of a motor-car transmission that had covered over 100,000 miles. The high-carbon steel gears in this car still showed the original tool marks. Not long ago a designer of machine tools commented on the apparent softness of some hardened high-carbon gears, but found after several months of hard service that they still showed tool marks, thus proving hardness ample for wear.

"2. In service, especially for clash gears, the superiority of these gears is most marked. On the clashing faces, case-hardened gears are likely to have the hard case chipped off, thereby exposing the soft core to the impact of clashing. The hard chips fall into the gearing and may find their way into bearings, thus causing trouble. High-carbon steel gears with a uniform hardness throughout do not chip, nor do they 'dub over.'

"3. The heat treatment of high-carbon steel gears is much simpler than that required for proper case hardening. It is shorter, less costly and produces a more uniform product, and as the gear is heated but once for hardening, as compared with three times for case hardening, the finished gear is certain to be freer from warpage. The cost of proper case hardening is not generally appreciated, but it has been found that a case-hardening steel must cost three to four cents per pound less than a regular high-carbon hardening steel, if finished gears made from both materials are to cost the same.

"With all heat-treated gears, little points in design are important. The gear-teeth should not be undercut, for if the section at the root-line is smaller than at the pitch-line, greater hardness and brittleness is produced where least desired. Great differences in section should be avoided wherever possible, so as to do away with excessive warpage. Sharp edges and angles, even in key-ways, are the cause of internal hardening strains which frequently result in failures; hence, wherever possible, a fillet should be used in place of a sharp angle."

**Case-hardened Gears—Treatment.**—The steel for a case-hardened gear should be low in carbon, preferably under 0.25 per cent.; should be carburized so as to produce a case of a depth of about  $\frac{1}{64}$  or  $\frac{1}{32}$  inch and contain a maximum carbon concentration of about 0.9 per cent.; and should then be suitably heat treated. Since the principles of case hardening have been described elsewhere,

it will be necessary here only to outline the process, which is as follows:

(Gear blank).

1. Anneal.
2. Rough machine to approximate size
- (3. Light re-anneal.)
4. Finishing machine.
5. Carburize at about 1600°–1650° F.
6. Cool slowly in carburizing box.
7. Reheat and oil quench from 1550–1625° F.
8. Reheat and oil quench from 1350–1425° F.
- (9. Temper, if desired, to not over 400° F.)

The temperatures given are only approximate, depending upon the analysis of the steel, the mass of the steel, the results desired, and various other factors. Nos. 3 and 9 may be omitted if desired.

**Oil-hardened Gears—Treatment.**—For the higher-carbon steels used for oil-hardened gears it is always advisable to give the gear blanks a preliminary treatment to develop the highest qualities of the alloy steels and the greatest uniformity in their physical properties. This treatment will also give the greatest “softness” of which the steel is capable. This preliminary treatment (before machining) is:

1. Quench in oil from about 150° to 200° F. over the critical range.
2. Quench in oil from about 50° F. over the critical range.
3. Anneal at a temperature about 75° F. under the critical range.

If this preliminary treatment is not given, the gears blanks should be given a thorough annealing. The slight reanneal after rough machining and before the final cut is optional; it always helps, however.

The final treatment consists in an oil-hardening and tempering process. For the majority of alloy steels this quenching is done from a temperature about 50° F. over the critical range; in the case of chrome vanadium steels, however, the best results are generally obtained by the use of a higher temperature. The temperatures generally used for the standard types of alloy steels for automobile gears, approximating 0.45 to 0.55 per cent. carbon, are about as follows:

## Chrome nickel steels:

- 1.5 per cent. nickel, 0.5 per cent. chrome, 1400° F.
- 1.75 per cent. nickel, 1.0 per cent. chrome, 1425
- 3.0 per cent. nickel, 0.75 per cent. chrome, 1375
- 3.5 per cent. nickel, 1.5 per cent. chrome, 1400

## Nickel steels:

- 3.5 per cent. nickel . . . . . 1400° F.
- 5.0 per cent. nickel . . . . . 1375

## Chrome vanadium steel:

- Type "D" (1.0 per cent. chrome, 0.8 per cent. manganese, 0.16 per cent. vanadium) . . . . . 1575° F.

## Silico-manganese steel:

- 1.5 per cent. silicon, 0.7 per cent. manganese 1550° F.

The usual precautions should be observed such as uniform and thorough heating, protection from oxidation, etc. Further, the gear should be quenched in the direction of its axis so that the oil can be made to circulate around the teeth, etc. The notes given under "Milling Cutters" <sup>1</sup> might also be of interest in their bearing upon gear treatment.

The tempering is usually done at a temperature of 400° F. or upwards, depending upon the nature of the steel and upon the results desired. It should again be stated that a longer tempering at the lower temperature is preferable to a quicker and shorter tempering at a higher temperature. Thus, if a gear were to have the temper drawn quickly, the teeth, which should be the hardest, will be softer than the hub, which will remain brittle; with a longer heating at a lower temperature this will not be the case, since the whole gear will have responded throughout. Similarly, for these reasons, it is inadvisable to temper gears "by color," but to use an oil bath or a mixture of low melting-point salts.

For gears made of alloy steel with only about 0.30 per cent. carbon the tempering operation is usually omitted. It is always best, however, to reheat the oil-quenched gears in boiling water for a short time in order to remove the hardening strains; such treatment will have little or no influence on the hardness and strength. The quenching temperature for such steels will of course be higher by some 50° or 75° than that given under the 0.45-0.55 per cent. carbon steels.

<sup>1</sup> Cf. Ch. XVI.



## SPRINGS

The usual analysis for carbon steel springs is approximately:

Carbon.....	0.90 to 1.10 per cent.
Manganese.....	under 0.40
Phosphorus.....	under 0.04
Sulphur.....	under 0.04
Silicon.....	up to 0.25

It is dangerous to allow the percentage of carbon to run up to 1.25 per cent. (as is sometimes done), on account of the possibility of the formation of free cementite, which is an extremely brittle constituent. A crack might easily start in an area of cementite and when once started would follow through the cementite to the outer surface. Lower carbons would preclude the presence of free cementite. Finely divided cementite would also be less dangerous, and this could be obtained by hardening at a lower temperature (about 1400° F.), since crystallized and granular cementite can only be obtained by heating for a prolonged time at a high temperature.

Aside from improper analysis, the majority of spring failures and troubles may be laid to abnormally high temperatures for heating for fitting followed directly by quenching from whatever temperature the steel may happen to be at; and then, as if this were not bad enough, to temper by "flashing." From general knowledge it appears that the maker of springs has not kept pace with improvements in spring steel and with the increased severity of the duty expected of springs.

The old practice of high temperatures and of forming and hardening springs with a single heating cannot be persisted in if maximum quality and service are to be secured. The "practical" spring-fitter generally heats the steel to about as high a temperature as it will take without burning. Its effect upon the structure of steel has been explained in preceding chapters, and also above in its relation to very high-carbon spring steel.

But even assuming that the proper temperatures have been used in fitting, the time taken to go through the forming operation is sufficient to give the steel a chance to cool down to a temperature which will not give the most satisfactory results in hardening. The steel is not of uniform temperature over its length so that, if it be quenched directly after forming, it will probably lock up internal

strains of uncertain magnitude—to say nothing of the insufficient hardening if the temperature be under that of the critical range. In other words, the spring should be put back in the furnace again (it being generally preferable that the maximum temperature for forming shall be the same as that required for hardening) and reheated for a few minutes so that it will be heated uniformly throughout at the right temperature. If high temperatures have been used for forming it will be advisable to allow the steel to cool to a temperature under that of the Ar range before reheating for hardening; if this is not done the steel will retain the coarse grain-structure characteristic of the high heat for forming. If it is found that the steel departs from its shape at all during this reheating, it may be put through the rolls again previous to quenching, the time occupied being small compared with that for the original bending. The spring should then be quenched in some good, heavy tempering oil.

For drawing the temper it is never advisable to use the process known as “flashing.” The practice of replacing the steel, after quenching, in a high temperature furnace until the outside of the steel reaches the desired temperature is one which cannot be too strongly denounced, because of the impossibility of uniform treatment. No time is allowed for the heat to soak to the center, with the result that the hardness *increases* from the outside—a most undesirable condition. All spring steel should be drawn back in a suitable low-temperature furnace maintained at the proper temperature. The steel should be kept in the furnace for a time sufficient to allow of a uniform heating throughout. Lead baths and salt baths are also used considerably for this work.

The proper temperatures for treating carbon spring steel have been given considerable attention by the American Society for Testing Materials. Their experiments were made with test specimens  $1\frac{3}{4}$  by  $\frac{3}{8}$  by 14 ins. long with straight edges, and analyzing about 1.10 per cent. carbon. The results of these tests (1911) are given in the tables on page 394.

It is apparent that at a quenching temperature of 1500° F. the maximum results are obtained with a drawing temperature of about 600° F., while with a quenching temperature of 1650° F. the maximum elastic limit was found with a drawing temperature of about 800° F. In the former group, Series A, 1500°–600° F., it was found that the angle of bend at rupture showed an average of slightly over 59°, there being considerable variation between the specimens; while in the second group, Series B, 1650–800° F., the

average angle was slightly over  $103^{\circ}$ , without any specimen going below  $76^{\circ}$ . These results are particularly interesting in view of the fact that the critical range of these steels is about  $1350^{\circ}$  F., and that one would naturally expect that a temperature of about  $1400^{\circ}$  F., i.e., slightly over the critical range, would give the best results. Whether or not such would show up in vibratory tests is a question which should be given attention.

### TRANSVERSE, HARDNESS AND BENDING TESTS OF CARBON SPRING STEEL

#### *Series A, Quenched in oil from $1500^{\circ}$ F.*

Temper Drawn to Deg. F.	Elastic Limit, (transverse) Lbs. per Sq. In.	Hardness.			Bend Test, Angle Bent through at Rupture, Deg.
		Scleroscope.		Brinell.	
		On Flat.	On Edge.		
425	129,137	48.5	47	370	181
600	136,440	46	50.5	388	60
835	131,017	43.5	49.5	351	86
1025	96,852	34.5	39	268	152
1230	105,400	34	37	282	167

#### *Series B, Quenched in oil from $1650^{\circ}$ F.*

450	130,922	46	52.5	394	90
625	134,232	43	57	371	82
820	141,147	46	56	389	104
1025	126,320	42	50	371	108
1210	83,457	31	36.5	260	180

### ALLOY STEEL SPRINGS

The service conditions to which automobile springs are subjected are extremely severe, for they have to sustain the shocks at speed of the irregularities of the ordinary highway, built for slow-moving, horse-drawn vehicles. The necessity for high elastic limit, combined with great toughness and anti-fatigue qualities, make the use of alloy steel almost mandatory.

The alloy steels in use are of the same analysis of those previously given under the heading of "Oil-hardened and tempered Gears" (q.v.). The quenching temperatures are likewise the same as there given, but the drawing temperatures are higher—generally from  $850^{\circ}$  to  $1025^{\circ}$  F. As far as *static* strength is concerned, the majority of the now common alloy compositions will give about the same test values, approximately:



Tensile strength, lbs. per sq. in. . . . .	190,000 to 250,000
Elastic limit, lbs. per sq. in. . . . .	170,000 to 225,000
Elongation, per cent. in 2 ins. . . . .	15 to 6
Reduction of area, per cent. . . . .	45 to 20

Some of the alloy steels, and particularly the chrome vanadium type, require annealing before shearing. The chrome vanadium steels used for springs are readily susceptible to "temper," and it is likely that the rapid air cooling of small flats after they leave the rolls will cause them to be brittle, thus giving a great amount of trouble in shearing. The annealing of this chrome vanadium steel is done by bringing the steel up to a full cherry-red heat in the furnace (about 1475° F.) and allowing it to cool slowly after being maintained at this temperature for a sufficient time to allow of uniform heating.

The new steels cannot be handled just like the old carbon steel springs and still obtain from them the maximum development of their powers. However, the new steels, being in general lower in carbon, will stand much abuse in heat treatment and still produce springs of quality undreamed of a decade ago. While as a class spring-makers have been driven to the use of alloy steels, they have not as a class been forced to handle them scientifically.

Alloy steels especially should not be heated any higher for forming than is absolutely necessary. Then they should always be *reheated* to the proper temperature for quenching in order to make sure that the entire steel is uniformly heated throughout to that temperature, which must be exact. The same remarks about tempering as given under carbon steel springs likewise apply here, and with added emphasis.

#### OIL-WELL BITS

Bits used for drilling oil wells, gas wells, etc., represent that class of large implements requiring "end heats." The hardening of these bits is necessarily an operation to be carried out in the field, since the bits require a more or less frequent dressing and must be rehardened after each heating. An extremely hard end and face, together with a strong, tough core and shank are the principal requirements for this work.

About 6 or 8 ins. of the bit is carefully heated in the fire (usually a common blacksmith forge), to the proper temperature—usually about 1500° F. Higher temperatures should not be used unless absolutely required by the nature of the steel. Any scale should be

carefully and quickly brushed off before quenching. The bit is then removed from the fire and allowed to rest in a bucket of coarse salt for a second or two. This salt treatment may be omitted, but it undoubtedly gives better results; the direct use of brine is generally too severe for most bit steels.

A box or trough should previously be fitted with a wooden grating made of slats, the top of which will be about 3 or 4 ins. under the surface of the water in the box. Some drillers add vitriol to the water quenching bath to obtain a greater hardness. The bit should then be quickly lowered vertically into the cold water until it rests upon the wooden grating, and should be allowed to remain there until cold.

The precautions to be observed are: (1) Lower vertically, in order to obtain an equal hardness on both faces of the bit; (2) do not quench to a greater depth than 3 or 4 ins.; (3) do not move the bit nor splash the heated part of the shank with water; (4) allow the steel to remain in the water until cold, generally over night. Although the surface of the water bath may steam, it will generally be found that directly beneath the surface the water is cold, and likewise the end of the bit. Splashing the heated part of the bit with water has a tendency to draw the temper of the faces. Immersion to a greater depth than 3 or 4 ins. is apt to give a soft bit. If these precautions are carefully observed, and the steel is of the right analysis, a bit with a glass-hard surface and a strong, tough core will be obtained. Such bits require no tempering, and should not chip off.

Oil-well bit steel will vary between 0.50 and 0.80 per cent. carbon and manganese, low phosphorus and sulphur, up to 0.25 per cent. silicon, and the addition of about 0.5 per cent. chrome for the lower carbons. The chrome bit steel, if of the proper carbon-manganese-chrome composition, will undoubtedly give the best service. The following analyses are characteristic of American oil-well bits used and giving good service:

Carbon.	Manganese.	Phosphorus.	Sulphur.	Silicon.	Chrome.
0.73	0.61	0.017	0.030	0.14	
0.59	0.17	0.010	0.015	0.13	
0.83	0.65	0.010	0.021	0.13	
0.60	0.51	0.012	0.019	0.01	0.56
0.54	0.53	0.007	0.021	0.006	0.51
0.49	0.56	0.010	0.016	0.008	0.52

## SAFE AND VAULT STEEL

Safe and vault steel may be taken as representative of that class of material involving different steels welded together, but for which the proper treatment of one analysis will be sufficient for both. Steel for safes and vaults consists of alternate layers of soft and hard steel, and is known to the trade as "three-ply," "five-ply," etc. By having these alternate layers there is obtained, under suitable treatment, a metal which will have sufficient ductility (due to the soft layers) to resist explosive forces, and at the same time be impenetrable to drilling, sawing or other machine operations (due to the "hard center"). The soft layers are made of ordinary low-carbon or "soft" steel, while the hard centers will analyze about 0.85 to 1.05 per cent. carbon and manganese, with or without the addition of chrome.

The plate is first machined or ground to size and the necessary holes drilled, threaded, and plugged with fire-clay for protection. The plate is then placed in a suitable heat-treatment furnace, and thoroughly heated to 1400° to 1500° F., depending upon the composition of the hard layer. It is extremely important that ample time be allowed for the heat to penetrate and thoroughly heat the high-carbon steel, for it is upon the hardness of these layers that the full value of the finished plate will depend. The majority of the cases in which the necessary hardness was not obtained which the author has investigated have been due to an insufficient length of heating rather than to any fault in the analysis of the steel.

The plate is then quickly removed from the furnace by a crane or hoist and quenched in *cold* water. As the hardness is largely dependent upon the rapidity with which the steel is cooled through the critical range, arrangements should be made to obtain a constant supply of cold water in contact with the steel during the quenching operation. If the quenching is done in a tank, the inlet supply should be large enough always to keep the water cold—the warm water being taken away from near the top of the tank. In this case the plate is quenched vertically; particular care should be used in getting the *whole* plate into the water as quickly as possible, and in an absolutely vertical position, if warpage is to be avoided. As soon as the initial immersion is accomplished the plate may be swung to and fro in the tank to aid in the heat removal. Other plants quench by means of water sprays, the plate being supported on a horizontal



rack; with this method of cooling the water supply should be sufficient to remove the steam as soon as it is formed.

The plates are not tempered or drawn. Specifications require that the best high-speed steel drill shall not penetrate the hard-center layers.

#### STEEL CASTINGS

In the mad rush for alloy steels and their heat treatment but little attention has been given to the treatment of steel castings. And yet there is an opportunity for as great, if not greater, improvement in these parts as in forged or rolled sections. All steel castings should be annealed or oil treated, not only to remove the casting strains, but also to get the metal into the best possible condition. Due to the method of fabrication, the rapid cooling of thin sections and the slower cooling of adjacent thicker sections must inevitably produce casting strains of a more or less intense nature. Similarly and coincidentally, the structure of the metal must inherently be poor: the grain will be coarse instead of fine and "silky," the metal will tend to have low ductility and brittleness, and the physical properties of the steel as a whole will vary considerably. Unlike forgings and rolled sections, castings are not generally subjected to any reheating and elaboration, so that the metal must have those properties characteristic of moderate cooling from high temperatures.

Thus the usual specifications for steel castings, in which the low ductility will be apparent, will call for:

Tensile strength, lbs. per sq. in. ....	85,000
Elastic limit, lbs. per sq. in. ....	45,000
Elongation, per cent. in 2 ins. ....	12
Reduction of area, per cent. ....	18

Even the now common addition of titanium or vanadium will not serve to eliminate entirely the necessity for subsequent treatment. Annealing, or better still, a full heat treatment, is mandatory.

Contrary to the ideas held by many "practical" hardeners, the principles of treating steel castings in no wise differ from those of steel forgings of the same section and analysis. The main difficulty encountered is that caused by the length of time required for the diffusion of the ferrite and the equalization of the metal as a whole. Castings usually require considerable time for this to take place because of the tendency of the metal to return to its original molecular arrangement and structure during slow cooling. Thus

much of the unsatisfactory annealing is, technically speaking, due to the segregation of the ferrite.

It is therefore necessary, in annealing steel castings, to (1) heat well over the upper critical range, (2) for a length of time sufficient to obliterate entirely the previous structure and crystallization, and followed by (3) slow cooling. The proper annealing temperature for the ordinary machinery castings will be between 1500° and 1600° F., depending upon the carbon content.

If the annealing is preceded by normalizing, i.e., air cooling from a temperature considerably above the upper critical range—say 1800° F.—the length of time required for the subsequent anneal will be considerably shortened, besides improving the steel.

For castings with the carbon on the lower side of 0.25 or 0.30 per cent., or for castings of considerable size, air cooling from about 1600° F. will usually produce good results.

The best method, however, is that of oil quenching and annealing or toughening—either with or without a previous normalizing. The castings should be heated as directed under annealing, quenched in the proper manner in oil, and then reheated to the temperature which will give the combination of strength and ductility desired. A drawing temperature of 1250° F. will produce the most ductile steel.

#### STEEL WIRE<sup>1</sup>

The principal heat treatments used in the manufacture of wire are: 1, annealing; 2, patenting; 3, hardening and tempering.

Annealing serves to accomplish three important functions: 1. To remove the effects of hardening due to cold work in wire drawing or cold rolling, thus making the steel ductile and soft. Annealing for this purpose covers principally the low-carbon wires, those with carbon 0.25 per cent. and under. 2. To refine grain—applied principally to the higher-carbon rods and wires, those with carbon 0.30 per cent. and over. 3. To obtain definite structure in the finished material—applied principally to the higher-carbon wires, those with carbon 0.30 per cent. and over.

When a steel wire rod of the structure shown in Fig. 207 is subjected to the wire-drawing process, a marked change in the grain structure takes place. With each successive draft, the grains stretch out in the direction of drafting until a point is reached when the

<sup>1</sup> From a paper by J. F. Tinsley, American Iron and Steel Inst., 1914, and The Iron Age, May 28, 1914.

grains have been elongated to the limit of their ductility. If subjected to further strain by further drafting they will part and the wire will break. Before this brittle condition is reached, therefore, it is necessary to heat treat the wire by subjecting it to what is known in the wire business as a "process annealing."

The effect of wire drawing in elongating the structural grain of the steel may be seen by comparing Figs. 207, 208 and 209. Fig. 207 shows the structure of the rod before drawing; Fig. 208 shows the structure after a 15 per cent. reduction from the rod; and Fig. 209, the structure after a 60 per cent. reduction from the rod. All of these micrographs represent sections taken from a plane parallel to the axis of the rod or wire, not cross-sections. The reason for the marked difference in grain shown in Figs. 207 and 209 may be grasped more clearly when it is appreciated that Fig. 209 represents a wire reduced in the wire-drawing process to such a degree that it has become elongated  $2\frac{1}{2}$  times the original length of the rod.

Process or "works" annealing consists in heating the wire to a certain temperature, maintaining that temperature until the entire mass of steel is thoroughly heated through, and finally cooling down. In the most common of all annealing—that to remove the effects of cold work such as drawing—it is not necessary to reach the critical temperature, which is  $1300^{\circ}$  F., or higher, depending on the carbon content. A temperature of  $1100^{\circ}$  F. is entirely sufficient to relieve the strained condition of the grain shown in Fig. 209. Fig. 210 shows the same wire that is depicted in Fig. 209 after annealing at a temperature below the critical range.

In the annealing process the strained and elongated grains shown in Fig. 209 break up and rearrange themselves to form a new grain structure as shown in the micrograph. The annealed steel of the structure shown is now in excellent condition to withstand further cold work in reducing it to finer sizes; or, if already at finished size, is in good condition to meet the demands of annealed wire service.

The effect of reduction of section incident to wire drawing on the tensile strength and ductility of steel wire, and the marked change brought about in these characteristics by annealing, as just outlined, is shown in Fig. 216. This table is based on drafting and annealing practice in reducing a low-carbon steel rod—in this case 0.10 per cent. carbon—to a fine size of wire. It will be noted that between 80 per cent. and 90 per cent. reduction from the rod or annealed wire can be taken before annealing is necessary.



It is found in practice that in cold drawing from a soft rod or annealed wire, the increase in tensile strength is a direct function of the amount of cold work, almost independent of other conditions.

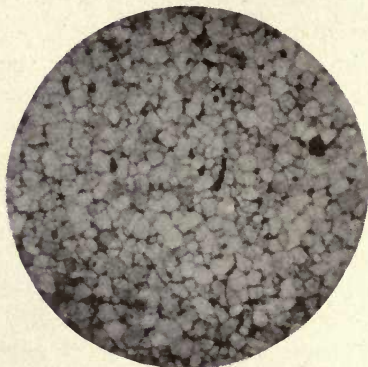


FIG. 207.—Annealed (0.08 Carbon) Steel. (Tinsley.)

Annealing practically brings the rod or wire, regardless of size, back to its original condition with regard to tensile strength and ductility. It will be noted that the final annealing does not bring



FIG. 208.—Steel Wire (0.08 Carbon)  
Given One Draft; 15 per cent.  
Reduction from Rod. (Tinsley.)

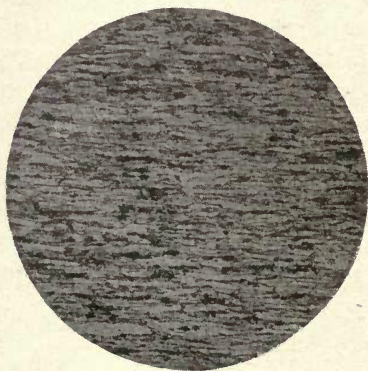


FIG. 209.—Steel Wire (0.08 Carbon)  
Given Several Drafts; 60 per  
cent. Reduction from Rod.  
(Tinsley.)

the tensile strength as low as previous annealing. This is due simply to the fact that in annealing the fine sizes it is usual, in order to avoid the mechanical sticking of the wire in coils, to anneal at slightly lower temperatures than in ordinary process annealing.

The second important function of annealing is that of refining grain, and its practical application in the wire mill covers principally the medium- and higher-carbon steels. The structure of wire rods with regard to size of grain is dependent upon the temperature at which the rods are finished in the hot rolling mill and upon the rate of cooling through the critical temperature of the steel. In steel of low carbon this is not of as much importance as in the higher-carbon steels, for the reason that the ordinary finishing temperature variations of good rolling-mill practice have less effect on grain structure of soft rods, and therefore less effect on their physical properties. In higher-carbon steels a fine grain is important, for it is this structure that makes for such steels their field of usefulness, where high strength, high elastic limit and toughness are required.

Theoretically, the ideal structure would be obtained if the entire rod could be finished at about the critical temperature. But this is, of course, impracticable, for the reason that it is impossible to regulate the finishing temperatures so closely, and for the additional reason that there is, necessarily, particularly in rolling very long lengths of very small sections, a marked difference between the finishing temperatures of the first and last end of a rod. The higher the finishing temperatures above the critical range the coarser the grain, and the coarser the grain the more does the steel lack the qualities that give it value. In order to destroy the coarse or uneven structure that may be created as just described, it is necessary to anneal the steel by heating it just above its critical temperature and slowly cooling it down.

The effect of overheating in coarsening the grain structure of a 0.45 per cent. carbon steel and the refining influence of this type of annealing is shown in Figs. 211 and 212.

The third and last class of annealing to be described—that to obtain definite structure—is one of comparatively recent development in the steel-wire industry and one which promises to be of considerable value. Annealing of this type is applied principally to the higher carbon wires. Since the structure of such wires can be varied considerably within a small range of annealing temperatures, it covers specific products and not general classes, as would be the case in regard to the two previously described types of annealing, Figs. 213 and 214 illustrate excellently this special type of annealing. These photomicrographs show the structures of two annealed pieces of the same coil of high-carbon wire, in which the annealing temperature of the one specimen was 1300° F., and of the other 1250° F.



It is impossible to identify the structure by a simple observation of the fracture, which is the ordinary rough-and-ready method; nor is it possible to regulate annealing temperatures so closely without the use of pyrometers.

In passing to the next great class of heat treatment applied to steel wire, patenting, it is interesting to note that we likewise pass to another class of wire as regards grading by carbon content. It naturally covers the medium-carbon steels, being employed chiefly on carbons between 0.35 and 0.85 per cent. In the medium-carbon steel wires strength and toughness are required for both process and finished wire. Patenting makes possible this combination of strength and toughness, and to this process is due in large measure a broad field of application for steel wire.

The high strength and toughness of patented wire are due to its carbon condition and to its peculiar structure. The first step in the patenting process is to heat the wire to a temperature above its critical range. The degree of heating is regulated according to the carbon content of the steel, the size of rod or wire, and the time the material is subjected to the heat. After sufficient heating, the next step is to cool the material rapidly below its critical range, the structure obtained depending upon the rate of cooling. In practice, patenting is usually conducted as a continuous operation, the wire being led through the heated tubes of a furnace and cooled by being brought into the air or into a bath of molten lead comparatively cool but seldom under 700° F.

A better understanding of the structure of a patented wire may be had by a comparison of the structure obtained by slow and by rapid cooling. If the steel after being heated is allowed to cool slowly through the critical temperature range, the homogeneous pre-existing solid solution of iron and iron carbide separates into a heterogeneous mixture of two constituents, resulting in the plate-like structure called "pearlite." In a patented wire, part of the carbide of iron is in solid solution and the remainder, while not in solid solution, has not had time to form into plates. The difference in structure between slow and rapid cooling is seen in Figs. 213 and 215. The photomicrograph of the patented wire shows, as a result of the rapid cooling, a structure that might be termed nondescript. Metallographists will recognize the structure as "sorbite," which, in the cooling of the higher-carbon steels from above the critical temperature, is that stage of transition just preceding the pearlitic, the final condition of annealed steel as shown in Fig. 213. The patented



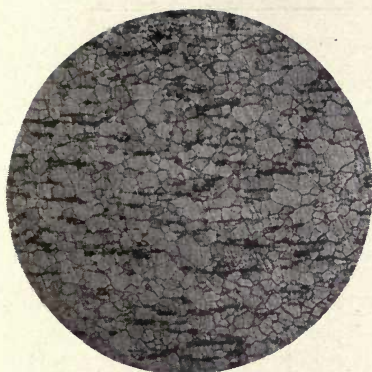


FIG. 210.—Steel Wire (0.08 Carbon) Hard Drawn and then Annealed below the Critical Temperature. (Tinsley.)

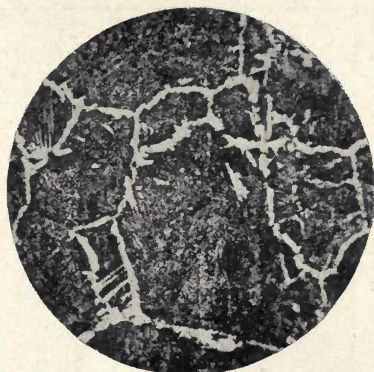


FIG. 211.—Steel (0.45 Carbon) Over heated. (Tinsley.)

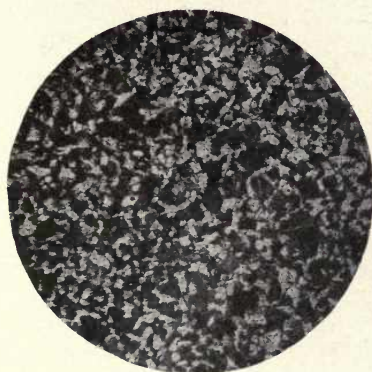


FIG. 212.—Steel (0.45 Carbon) Annealed. (Tinsley.)



FIG. 213.—Annealed (0.85 Carbon) Steel. (Tinsley.)

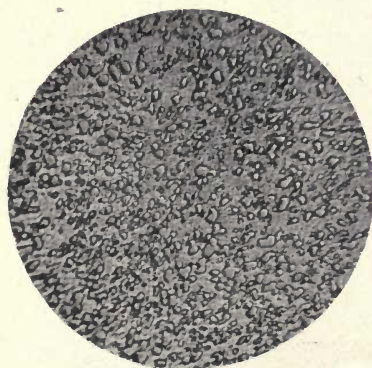


FIG. 214.—Specially Annealed (0.85 Carbon) Steel for Globular Structure. (Tinsley.)

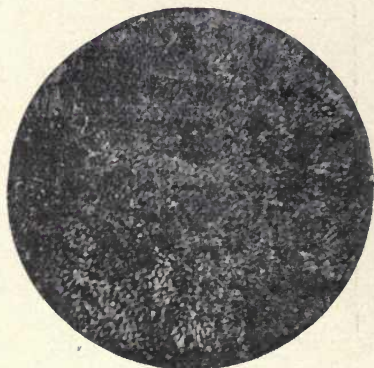


FIG. 215.—Patented (0.85 Carbon) Steel. (Tinsley.)

CONDITION OF MATERIAL	GREEN ROD #5 GA. .207"	FIRST DRAFT	THIRD DRAFT	PROCESS AN-NEALED	FIRST DRAFT	THIRD DRAFT	FIFTH DRAFT	PROCESS AN-NEALED	FIRST DRAFT	THIRD DRAFT	FIFTH DRAFT	SEV-ENTH DRAFT	AN-NEALED
PER CENT. REDUCTION BY DRAWING	0	47	82	0	35	70	85	0	21	62	80½	88½	0
TENSILE STRENGTH POUNDS PER SQ. IN.	68 000	113 000	150 000	60 000	93 000	130 000	145 000	62 500	82 000	124 000	143 000	151 500	68 000
PER CENT. ELONGATION IN TEN INCHES	25	2½	1½	30	3	2	1½	28	3½	2	1½	1	25

Fig. 216—Showing effect of cold-drawing and annealing on the physical properties of low-carbon (0.10 per cent.) steel.

Note—Dead soft annealing gave a tensile strength of 50,000 lbs. per sq. in. and in elongation of 32 per cent. both at the first and second annealing.

CONDITION OF MATERIAL	GREEN ROD #5 GA. .207"	FIRST DRAFT	SECOND DRAFT	PAT-ENTED	FIRST DRAFT	THIRD DRAFT	FOURTH DRAFT	PAT-ENTED	FIRST DRAFT	THIRD DRAFT	FOURTH DRAFT	PAT-ENTED	FIRST DRAFT	THIRD DRAFT
PER CENT. REDUCTION BY DRAWING	0	28½	51	0	30	50½	65	0	30	66	76	0	30	66
TENSILE STRENGTH POUNDS PER SQ. IN.	95 000	122 000	146 000	115 000	143 000	163 000	176 000	128 000	156 000	190 000	208 000	156 000	184 000	218 000
PER CENT. ELONGATION IN TEN INCHES	10	2.9	2.8	8.2	2.8	2.7	2.6	7.8	2.0	1.9	1.8	6.0	2.0	1.9

Fig. 217—Showing the effect of cold drawing and patenting on the physical properties of higher-carbon (0.50 per cent.) steel.

Note—At the first patenting stage, process annealing gave a tensile strength of 70,000 lbs. per sq. in. and 18 per cent. elongation.



wire, therefore, represents an unsegregated condition as against the segregated or coarsely laminated structure of annealed wire. The high tensile strength of patented wire is due to the amount of carbon in solution, and its toughness to the fineness of the grain structure.

Patenting serves two important functions in the wire business: 1. In the process of manufacture, the removal of the effects of cold work, such as drawing. 2. In the finished wire to give, in conjunction with cold drawing, the required combination of strength and toughness. Strictly speaking, patenting is not necessary simply to relieve strain, for annealing would serve that purpose, but the structure obtained by patenting permits much further cold drawing than does the structure obtained by annealing. This is due primarily to the increased ductility and toughness of the patented wire. The effect of patenting as just described is shown in Fig. 217.

In wire making, hardening and tempering should be conducted usually as a continuous process. In the making of tempered wire the material is first run through the heated tubes of a furnace, then quenched quickly in a bath of oil or water, then run into the tempering bath of, say, molten lead, each wire being in continuous motion from the time it enters the heating furnace until it is wound on a reel. Hardening and tempering apply to the higher carbon steel wires—those in which the carbon range is from 0.65 per cent. to 1.00 per cent. With varying tempering temperatures between 500° and 1100° F., the tensile strength runs from about 340,000 lbs. per square inch to 150,000 lbs. per square inch. At the lower temperature the decrease in tensile strength is, as we should expect, much greater per 100° F. range than at the higher temperatures. From 500° to 600° F. there is a drop of 60,000 lbs. per square inch, while between 1000° F. and 1100° F. the drop in tensile strength amounts to only about 10,000 lbs. per square inch.

#### FORGING

No small percentage of the difficulty encountered in heat-treatment operations is due to improper forging methods, and oftentimes the heat-treatment operation is nothing more than a useless effort or attempt to get something out of a forged piece of steel that is not actually in it. Thus, the steel man is often blamed for the absence of quality in his steel that he actually put in it; and the heat-treatment man is blamed for his lack of ability to locate such qualities, which he properly assumes to exist, but which, nevertheless, the forge man took out by poor heating, unknown to himself or the other two.



The strongest language that could be employed in an attempt to describe the general average heat-treatment equipment, the methods of heating, and personnel, as they are actually known to exist, would be altogether too mild and ineffective for a proper description of the heating methods and equipment in the majority of forge shops in the country. As in the case of machine work, the design of the hammers, presses and other machine equipment has made rapid strides forward, but the two most important factors of the operation from the metallurgical end—namely, the man and the furnace—have either stood still or gone backwards. Many well-informed and experienced men claim that the caliber of forge men to-day is not what it was years ago, and that better quality of work was produced with the old-fashioned coal or coke furnaces, though at a higher cost, than at present with furnaces burning oil or gas. There appears to be something in this statement, particularly in view of the high quality work turned out in Europe, where the use of high-speed machines, oil or gas fuel, and efficiency production methods, are not as prevalent as here. If such a difference actually exists, it can invariably be traced to the personnel of the plant, because, as in most operations involving the skill of the operator as against the fixed movement of a machine, quality reflects the man and his knowledge of the work. But even so, we can and should be able to do better with fuel so closely linked with uniformity of temperature, steadiness of operation, and ease of control. If we do not, then it is up to the man or the furnace and not to the hammer or the fuel, which is in itself a good argument for improvement of the heating and human equations in the operation.

Two of the weak links in forging practice, from the metallurgical end, are the lack of uniformity and temperature of the heats and the method of handling stock in and out of the furnaces.

As a rule, the heats are altogether too high, with the result that, while the surface is apparently hot, there may be actually a "bone" on the inside. It is common practice to see a bar drawn from a furnace that will actually drip, and yet when placed under the hammer there will be indications of lack of heating on the inside. It is the inside of the bar that determines the physical properties of the final forging and not the outside; and there is nothing gained in these quick "wash" or surface heats. Slow, soft, soaking heats, affording plenty of time to heat up, are more desirable than the higher quick heats. The idea should be to maintain the temperature of the furnace as near as possible to that actually required to soften

the steel to the extent necessary for its proper shaping, and to give it plenty of time in the furnace thoroughly to soak at this temperature without overheating or oxidizing the outside. The fire should be soft and a little high in carbon, in order to reduce oxidation. The modern alloy steels do not require high, sharp, dripping heats, and the proper handling of them demands the slow, soft, non-oxidizing heats above referred to.

The general design of forge furnaces is far below the standard of heat-treating furnaces and is a point usually left to the forge man or to a bricklayer. It is common practice to see furnaces hot on one side and cold on the other. Also, to hear complaints of lack of ability to heat steel properly in a furnace in which the burners blast directly against the stock, which naturally keeps the stock nearest the burner cool and heats the pieces farther away. There are hundreds of such designs in use that have been turned out by furnace builders who ought to know better.

## CHAPTER XVIII

### PYROMETERS AND CRITICAL RANGE DETERMINATIONS

#### PYROMETERS <sup>1</sup>

**Pyrometers in General.**—The pyrometer has played a basic part in the development of intelligent heat treatment. In hardening rooms where pyrometers are not used, a discussion of any temperature treatment and instructions are given as the instructions must have been given in the Tower of Babel. There is no distinction or mutual understanding of terms, and until a pyrometer—and an accurate one—is in a hardening room, it is not possible for those interested in the heat treatment in that room to talk to each other in a mutually intelligible way. Of course, where one old hardener has been in charge for twenty years and the management decides to take a chance on his staying with them and living for another twenty years, it may be all right to have everything locked up in his head; but where matters are more extensively and more modernly conducted, it is necessary to have some language in which people can talk; and the pyrometer, by virtue of its temperature scale, which is a conventional scale of defined terms, affords the means of communication in a language that is mutually understood. In the same way it permits records to be kept for future reference. Where this is not done, men will be found trying to remember the heats at which they treated this, that or the other lot of steel; they cannot remember, and they are sure to get into trouble if they try to. The pyrometer has changed barbarian methods into civilized methods in a hardening room.

There is need for a greatly extended use of pyrometers of the best possible grade, but more especially for an intelligent use of them that will in some measure compensate for the skill in producing them

<sup>1</sup> It is the aim of this section to deal more with the rational use of pyrometers rather than with a detailed explanation of the theory and construction of the numerous instruments in commercial use for heat measurement. For a fuller explanation of the latter subject than is subsequently given, the reader is referred to standard reference books on the subject.



and the money involved in their installation. The pyrometer is not all-sufficient, nor it is the cure-all for the troubles of a hardening plant. There should be an education of the man to look upon pyrometers as gauges and indicators of the existence of energy, and as an aid to him in executing his work and not as a means of releasing him from responsibility accompanying the exercise of judgment.

The pyrometer has been of inestimable value in affording a means to check temperature, but—and aside from the correlation of results—its efficiency ends largely with that indication. The uniformity of heated product, however, depends upon the manner of applying the heat, which—with the method and cost of operation—is primarily a function of furnace design. It is possible to indicate a uniform temperature and yet not produce a uniformly heated product; and unless the heat is uniformly applied to the stock at the temperature indicated, then a uniform pyrometer reading is misleading and inconclusive. Thus an elaborate pyrometer system, with means for signaling variations in temperature and of recording these variations, is not conclusive evidence of accurate heating. The development toward better and cheaper results will be brought about by improved heating methods, even though the temperature recorded from any one point in a furnace chamber may be the same as that indicated from a similar point of another furnace less efficiently designed.

The time element is linked inseparably with all heating operations. A piece of steel can absorb heat only so fast and no faster. Only by operating the furnace so that the maximum temperature is maintained for the length of time necessary uniformly to heat the steel throughout to that temperature, is it possible to produce the best results. In other words, the composition and the mass of the steel must be correlated with the time element. First determine the length of time necessary, under standard furnace conditions, to produce the necessary results; then regulate the furnace by the aid of the pyrometer; and finally, place a clock beside the instrument and work the two together. The sooner the average heat-treatment man (and his superiors, for that matter) can be brought to realize that a pyrometer is almost valueless without the use of a time clock and common-sense observation of furnace conditions, the better.

**Thermo-Couples.**—For the usual operations in heat-treatment work involving temperatures of over 600° or 700° F., the thermo-

couple system is the most used. The principles upon which its use depends are simple. Expressed briefly, if the ends of two pieces of dissimilar metals (usually as wires) are joined together and one of the junctions (the "hot end") is heated, the other junction (the "cold end") being held at a constant temperature, a feeble electric current is generated in the circuit. This electromotive force, aside from being dependent upon the nature of the couple, is, for the thermo-couples in practical use, dependent upon the difference in temperature between the hot and cold ends.

In regard to thermo-couples, standard base-metal compositions will generally give satisfaction between 600° or 700° F. and 1800° F.; while above 1800° F. couples of platinum and platinum-rhodium should be used. All base-metal couples should be readily replaceable, and, more emphatically, interchangeable. All couples should be suitably protected with iron pipes from oxidation and rough handling.

**Position of the Thermo-Couple.**—The fact that a pyrometer may show that some particular portion of the heating zone is at the proper temperature is no proof that the steel is also at that temperature. The hot end of the couple may be so placed that it must inevitably be hotter than the hearth of the furnace, or hotter than any material placed on the hearth. This will be true if the end of the couple is exposed to the direct heat of the flame. It might therefore be concluded that the tip should be as near the work as is possible, so that both may attain the same temperature—and which is without doubt advisable in many instances. On the other hand, it has been noted in some cases in which the couples have been placed close to the work that the readings are not in accord with the temperature of the steel because the couples, being of smaller mass, take up readily the high peak of the flame temperature. There are certain instances where it has been found by experience desirable to locate the tip of the couple in a recess in the furnace wall where it was out of the course of the flame and thus dependent for its temperature upon radiation from the main body of the furnace lining and radiation from the work; under some circumstances such a position is preferable.

**Millivoltmeter vs. Potentiometer.**—By inserting into the thermo-couple circuit, at the cold junction, a suitable device for measuring the electromotive force, a reading may be obtained in millivolts; or, by suitable calibration, a reading directly in terms of temperature. This indicating instrument (the pyrometer) may be of

the galvanometer or millivoltmeter type, or of the potentiometer type.

The potentiometer in theory bears much the same relation to the millivoltmeter that the balance-arm scales bears to the spring scales. The constancy of both the spring scales and the millivoltmeter is entirely dependent upon the constancy of springs or of suspensions, and upon the absence of friction. The constancy of the potentiometer and of the balance-arm scales is dependent only upon the constancy of standard weights in one case and a standard electromotive force in the other. Standard weights are added to or removed from balance scales until a balance between known and unknown is obtained. Similarly in the potentiometer type varying fractions of a known and presumably standard electromotive force are opposed to the electromotive force of the thermo-couple until it is balanced just as a standard weight is moved along a scale arm for balance.

This is the potentiometer not as it is, but as we would like to have it. The standard cell will not stay standard if any current is drawn from it and, consequently, the e.m.f. of the standard cell is not opposed to the e.m.f. of the couple in potentiometers as made for any ordinary use. Another cell or battery is brought into use and the e.m.f. of that is opposed to the e.m.f. of the couple. Now this secondary cell varies in e.m.f. from week to week and day to day, and even hour to hour under use, and it is necessary continually to check this service cell against a standard cell and then to adjust for the differences that are creeping in all the time. The balance scales, therefore, instead of being operative with standard weights, have a sort of beaker of boiling water as the weight, which is continually boiling to less mass and which has to be filled up or adjusted every few minutes by comparing it with a standard weight, for the standard weight itself is not trusted on the scales nor is there any other weight, i.e., battery, that can be trusted on the scales that will not vary.

**Selection of Equipment.**—The selection of one type or the other is largely a matter for economic and technical consideration. In a word, the purchaser should consider the relation existing between (1) accuracy, sensitiveness and constancy, (2) ease of reading, and (3) the cost—both initial and of up-keep. There is also a psychological consideration that goes hand in hand with the above considerations and which should not be lost sight of: the millivoltmeter is a direct-reading instrument, which means that it is easy to read; the potentiometer requires a fair amount of manipulation and is



somewhat less easy to read. The question then is: Which instrument will the average furnace man read more frequently? No matter how accurate a pyrometer may be, its value is only in the use made of it.

**Cold-end Temperature.**—The cold-end temperature is a source of prolific error in some pyrometer installations. It should be remembered that all instruments are calibrated for a definite cold-end temperature, usually 75° F. If the cold end is in a position such that it receives the direct or radiating heat from the furnace, and

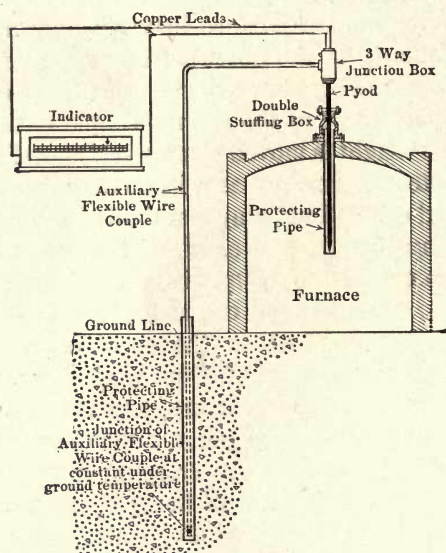


FIG. 218.—Compensating Cold End Temperatures with Auxiliary Couple.  
(Wilson-Maeulen Co.)

therefore varies in temperature, the indicated temperature at the instrument will be incorrect. For this reason the cold end should always be kept cool, and at as near a constant temperature as is possible. This compensation may be accomplished by having the cold end as near the ground as possible; or by letting a small stream of cold water flow over the cold ends; or by connecting an auxiliary couple of the same electromotive force as the furnace couple in opposition to the couple in the furnace, and running the auxiliary couple to an underground point at the bottom of a pipe driven a few feet into the earth as shown in Fig. 218. The potentiometer type equipment frequently carries the cold end directly to the instrument,

entirely eliminating the effect of fluctuating temperatures near the furnace.

**Pyrometer Standardization.**—One of the most important points in connection with pyrometers is the *necessity* for frequent and regular calibration of the thermo-couples. All base-metal couples should be standardized at least once a week, and oftener if possible. Further, new couples should always be standardized before use, since errors may frequently be found even in supposedly correct new couples.

There are two general methods for standardization or calibration of thermo-couples: (1) Checking against the melting- or freezing-points of known salts or metals, and (2) checking against a standard millivoltmeter or pyrometer.

**Standardization with Common Salt.**—An easy and convenient method<sup>1</sup> for standardization and not necessitating the use of an expensive laboratory equipment is that based upon determining the melting-point of common table salt (sodium chloride). While theoretically salt that is chemically pure should be used (and indeed this is neither expensive nor difficult to procure), commercial accuracy may be obtained by using common table-salt such as is sold by every grocer. The salt is melted in a *clean* crucible of fire-clay, iron or nickel, either in a furnace or over a forge-fire, and then further heated until a temperature of about 1600° to 1650° F. is attained. It is essential that this crucible be *clean*, because a slight admixture of a foreign substance might noticeably change the melting-point. The thermo-couple to be calibrated is then removed from its protecting tube and its hot end is immersed in the salt bath. When this end has reached the temperature of the bath, the crucible is removed from the source of heat and allowed to cool, and cooling readings are then taken every ten seconds on the millivoltmeter or pyrometer. A curve is then plotted by using time and temperature as co-ordinates, and the temperature of the freezing-point of salt, as indicated by this particular thermo-couple, is noted, i.e., at the point where the temperature of the bath remains temporarily constant while the salt is freezing. The length of time during which the temperature is stationary depends on the size of the bath and the rate of cooling, and is not a factor in the calibration. The melting-point of salt is 1472° F. and the needed correction for the instrument under observation can be readily applied. The curves in Figs. 219 and 220 illustrate the calibration of a correct and incorrect pyrometer.

<sup>1</sup> Carpenter Steel Co.

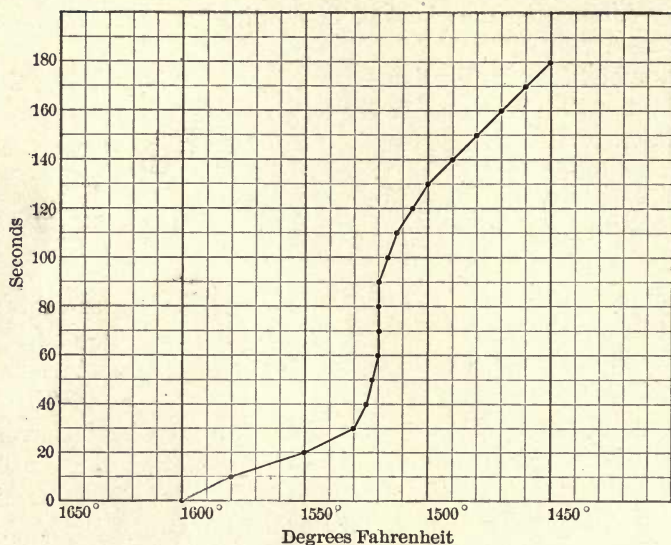


FIG. 219.—Diagram Showing the Calibration of a Pyrometer which Reads 45° F. Too High. (Carpenter Steel Co.)

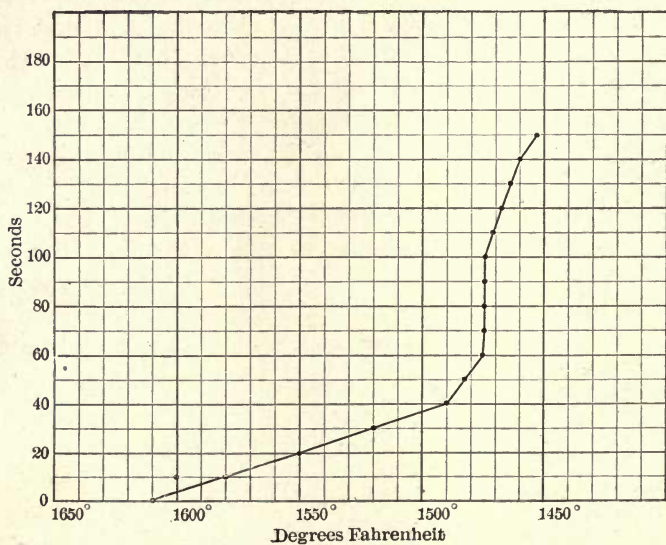


FIG. 220.—Diagram Showing the Calibration of a Pyrometer which is Correct. (Carpenter Steel Co.)



It should not be understood from the above, however, that the salt-bath calibration cannot be made without platting a curve: in actual practice at least a hundred tests are made without platting any curve to one in which it is done. The observer, if awake, may reasonably be expected to have sufficient appreciation of the lapse of time definitely to observe the temperature at which the falling pointer of the instrument halts. The gradual dropping of the pointer before freezing, unless there is a large mass of salt, takes place rapidly enough for one to be sure that the temperature is constantly falling and the long period of rest during freezing is quite definite. The procedure of detecting the solidification point of the salt by the hesitation of the pointer without platting any curve is suggested because of its simplicity.

**Complete Calibration of Pyrometers.**—For the complete calibration of a thermo-couple of unknown electromotive force, the new couple may be checked against a standard instrument, placing the two bare couples side by side in a suitable tube and taking frequent readings over the range of temperatures desired.

If only one instrument, such as a millivoltmeter, is available, and there is no standard couple at hand, the new couple may be calibrated over a wide range of temperatures by the use of the following standards:

Water,	Boiling-point.....	212° F.
Tin, under charcoal,	Freezing-point.....	450
Lead, under charcoal,	Freezing-point.....	621
Zinc, under charcoal,	Freezing-point.....	786
Sulphur,	Boiling-point.....	832
Aluminum, under charcoal,	Freezing-point.....	1216
Sodium chloride,	Freezing-point.....	1474
Potassium sulphate,	Freezing-point.....	1958

A good practice is to make one pyrometer a standard; calibrate it frequently by the melting-point-of-salt method, and each morning check up every pyrometer in the works with the standard, making the necessary corrections to be used for the day's work. By pursuing this course systematically, the improved quality of the product will much more than compensate for the extra work.

**Central Switch-boards.**—For plants in which there are a number of thermo-couples, one indicating instrument with a central switch-board may be used. As many as sixteen couples may be wired to one selective switch, the maximum number simply depending upon the elasticity of the system and the convenience of the operator.

A wiring diagram for such an installation is shown in Fig. 221. By throwing the switch from one contact to another the connection is made with each individual furnace. For large heat-treatment plants the time of one man is generally taken in attending to the system, he signaling the individual operators by means of lights and belts the relative temperatures in the furnace. We have previously commented upon such systems.

**The Central System.**—The Chalmers Motor Company operate their system,<sup>1</sup> having two central switch-boards with sixteen furnaces on a switch, as follows:

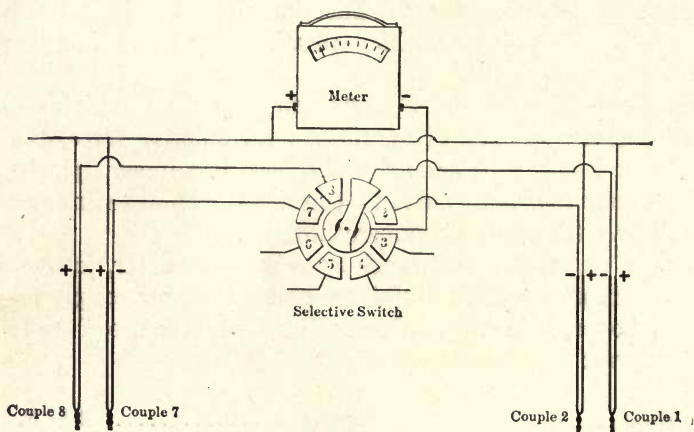


FIG. 221.—Wiring Diagram—Pyrometer and Selective Switch. Showing Four Couples Connected with the Switch, Openings for Four More. (Hoskins Mfg. Co.)

"We regulate the heat of the furnaces by a series of lights—each furnace having over it a red, blue and green light. These are used as follows: We will say that the temperature of an empty furnace which we are about to use is 1600° F. The loading of the furnace with forgings necessarily reduces the heat by radiation anywhere from 100° to 250°, depending upon the number of pieces put in the furnace. When we commence to bring the heat up again to the proper place and it gets to about 1575°, the man at the switch-board throws on a blue light, which means to the furnace operator that the heat is still considerably too low. When the temperature reaches about 1590° the blue and green light is turned on, which signifies to the operator that the furnace is still not quite hot enough.

<sup>1</sup> Personal Correspondence.

When the 1600° point is reached the green light is turned on; this is the O. K. light and means that the temperature is correct. The steel is then allowed to soak at this temperature for the time necessary to affect the whole mass. If the heat during the operation gets too high we use signals in an inverse manner, the red and green lights being thrown on. If it shows a dangerous rise in temperature the red light is thrown on. All of these lights are accompanied by the ringing of a loud bell in the heat-treating department, which automatically attracts the attention of the man operating the furnaces, who at once inspect their individual furnace lights to see if their temperature is correct."

#### DETERMINATION OF THE CRITICAL RANGES

**Critical Ranges.**—The practical importance of knowing the exact location of the critical ranges of steel to be treated is obvious. Their determination by means of pyrometers is based upon the fact that the changes taking place in the steel at those temperatures involve an absorption of heat during heating (the decalescent points) and a giving out of heat on passing through these ranges on cooling (the recalescent points).

**Decalescent vs. Recalescent Points.**—Before discussing methods, it should be stated that, for the majority of heat-treatment work, it is more important to know the location of the decalescent points than that of the recalescent points. This is for several reasons. To effect a complete change of the original structure of the steel, it must be at least heated slightly beyond the Ac3 range, regardless of the position of the Ar3 range. If the steel were to be heated only to the Ar3 range, a complete change in structure cannot take place, because the Ar3 range is always below the temperature of the Ac3 range. Further, the position of the Ar ranges is, experimentally at least, dependent upon the maximum temperature to which the steel is heated, upon the length of heating at that temperature, and upon the rate of cooling from that temperature.

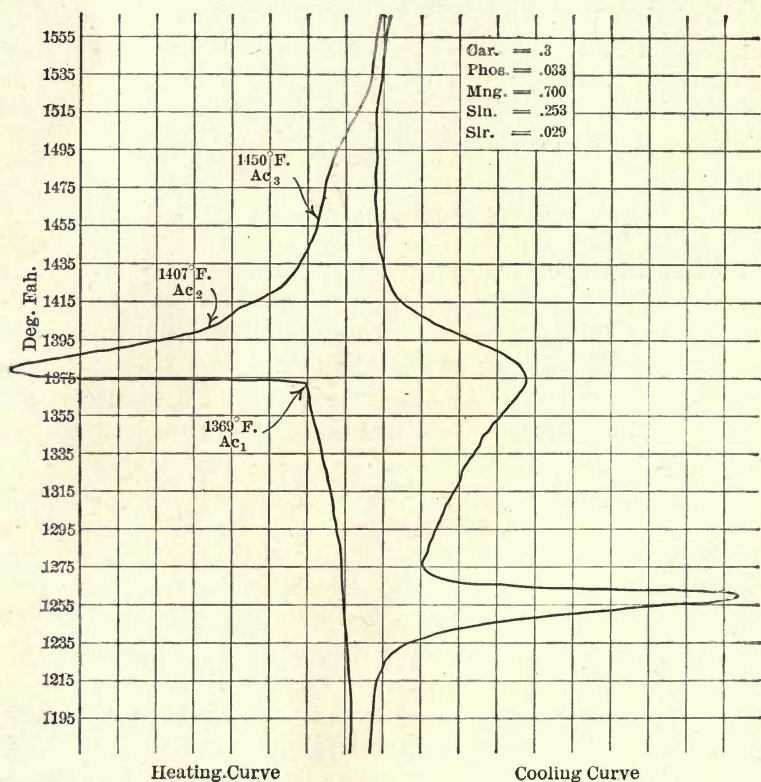
It should also be again stated that the determination of the upper critical range is of more importance than that of the lower critical range (A1), since the majority of hardening and annealing work demands a complete change of structure—which is obtained only above the upper critical range (Ac3).

**Temperature Difference Instruments.**—American-made instruments for determining the critical ranges of steel are based either



upon a temperature difference basis, or upon a direct record of a single instrument. The method used by the Leeds & Northrup apparatus, typical of the first class, involves the following points:

Two bodies are heated together in the same furnace, the one being the steel under test and the other being a body which will



Abscissæ—Temperature Differences between Sample and Non-recalcing Body.

FIG. 222.—Transformation Curves. (Leeds & Northrup Co.)

heat uniformly without undergoing any changes. If the bodies are in sufficiently close contact they will heat at the same rate and, barring changes in one which do not occur in the other, will remain equal in temperature. When, however, the steel undergoes an internal change involving absorption or liberation of heat, its temperature changes relatively to the other body and a temperature difference is set up between the two. Hence the apparatus for the location of

critical points by this method is designed to do two things: first, to measure the temperature of the sample; second, to indicate the temperature relationship between the sample and the unchanging body. A curve using temperatures as ordinates and temperature differences as abscissæ is the best way of making use of the results.

**Temperature Difference Records.**—Fig. 222 is a reproduction of such a plot. From the start of the test until  $1205^{\circ}$  the temperature difference is small and constant. When the temperature of  $1369^{\circ}$  is reached a sudden increase in the temperature difference takes place, the  $A_{c1}$  range. As soon as this sudden change ceases (i.e., transformation is completed), the sample and the unknown begin

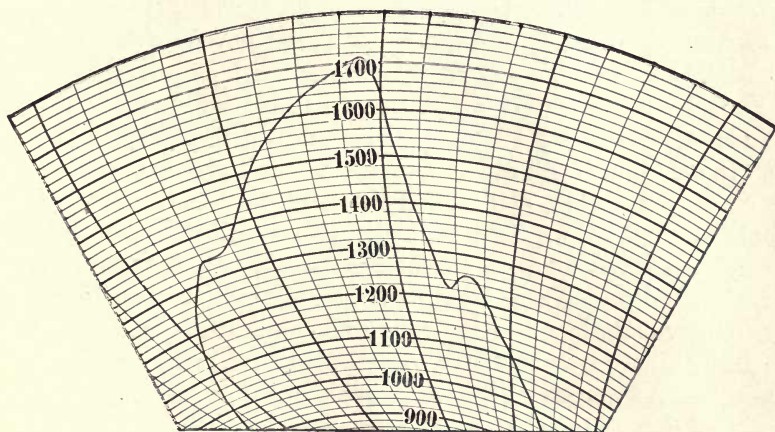


FIG. 223.—Critical Range Curve on a Direct-reading Apparatus. Carbon, 0.44 per cent.; Manganese, 0.53 per cent.; Phosphorus, 0.035 per cent.; Sulphur, 0.025 per cent.; Silicon, 0.028 per cent.

to equalize in temperature and the record of their decreasing difference follows a typical cooling curve between  $1380^{\circ}$  and  $1455^{\circ}$ , except at about  $1407^{\circ}$ , where the  $A_{c2}$  transformation begins to affect the record. At  $1407$ – $1410^{\circ}$  this  $A_{c2}$  change is completed. Again at  $1450^{\circ}$  there is a departure from a smooth curve; this is the beginning of the third transformation, which transformation is not completed until about  $1495^{\circ}$ . This is the  $A_{c3}$  transformation. On cooling, the reverse takes place, except that the two upper points occur closer together and appear as one. The lowest range is clear cut.

**Direct-reading Instruments.**—Fig. 223 shows a record obtained from a Bristol instrument. Leaving aside a discussion of the

scientific pros and cons, the three main objections to this *class* of instrument are: (1) the small area covered by the record, involving less accuracy; (2) lack of that degree of sensitiveness which is necessary to bring out the upper critical ranges; and (3) a curve showing direct temperatures instead of temperature difference.

**Practical Method for Determining Critical Ranges.**—For plants which have to determine the critical ranges but infrequently less costly apparatus may be used. The outfit should consist of a thermocouple made of small wires so as to respond quickly to any slight variation in temperature; the necessary leads; and a sensitive millivoltmeter or pyrometer with a finely divided scale. This instrument may also be used as a standard, or checking instrument, for calibration work. The specimens to be tested should be small so as to heat uniformly and quickly. These may be either a small cylinder, say  $\frac{3}{8}$  in. diameter by  $1\frac{1}{2}$  in. long, or duplicate pieces each  $1\frac{1}{4}$  in. long by  $\frac{1}{2}$  in. wide by  $\frac{1}{4}$  in. thick. In the former case the end of the couple is inserted in a small hole drilled through the axis of the cylinder to a depth of about  $\frac{1}{2}$  in.; in the latter case the pieces are clamped together, one on either side of the end of the thermocouple so as to form a tight contact. The specimen is then heated in any convenient manner, readings being taken every few seconds as the critical ranges are reached. When the indicated temperature is well above the upper critical range, the specimen is removed from the heat, allowed to cool not too rapidly, and readings taken to obtain the Ar ranges. The temperature readings, or difference in readings, should then be plotted against the time to obtain the necessary curves.



## TEMPERATURE CONVERSION TABLE

BY DR. LEONARD WALDO

Reprint from Metallurgical and Chemical Engineering.

C. °	0	10	20	30	40	50	60	70	80	90		
	F. °	F. °	F. °	F. °	F. °	F. °	F. °	F. °	F. °	F. °		
-200	-328	-346	-364	-382	-400	-418	-436	-454	-472	-490		
-100	-148	-166	-184	-202	-220	-238	-256	-274	-292	-310		
- 0	+ 32	+ 14	- 4	- 22	- 40	- 58	- 76	- 94	-112	-130		
0	32	50	68	86	104	122	140	158	176	194		
100	212	230	248	266	284	302	320	338	356	374	C. °	F. °
200	392	410	428	446	464	482	500	518	536	554	1	1.8
300	572	590	608	626	644	662	680	698	716	734	2	3.6
400	752	770	788	806	824	842	860	878	892	914	3	5.4
500	932	950	968	986	1004	1022	1040	1058	1076	1094	4	7.2
600	1112	1130	1148	1166	1184	1202	1220	1238	1256	1274	5	9.0
700	1292	1316	1328	1346	1364	1382	1400	1418	1436	1454	6	10.8
800	1472	1490	1508	1526	1544	1562	1580	1598	1616	1634	7	12.6
900	1652	1670	1688	1706	1724	1742	1760	1778	1796	1814	8	14.4
1000	1832	1850	1868	1886	1904	1922	1940	1958	1976	1994	9	16.2
1100	2012	2030	2048	2066	2084	2102	2120	2138	2156	2174	10	18.0
1200	2192	2210	2228	2246	2264	2282	2300	2318	2336	2354		
1300	2372	2390	2408	2426	2444	2462	2480	2498	2516	2534		
1400	2552	2570	2588	2606	2624	2642	2660	2678	2696	2714	F. °	C. °
1500	2732	2750	2768	2786	2804	2822	2840	2858	2876	2894	1	.56
1600	2912	2930	2948	2966	2984	3002	3020	3038	3056	3074	2	1.11
1700	3092	3110	3128	3146	3164	3182	3200	3218	3236	3254	3	1.67
1800	3272	3290	3308	3326	3344	3362	3380	3398	3416	3234	4	2.22
1900	3452	3470	3488	3506	3524	3542	3560	3578	3596	3614	5	2.78
2000	3632	3650	3668	3686	3704	3722	3740	3758	3776	3794	6	3.33
2100	3812	3830	3848	3866	3884	3902	3920	3938	3956	3974	7	3.89
2200	3992	4010	4028	4046	4064	4082	4100	4118	4136	4154	8	4.44
2300	4172	4190	4208	4226	4244	4262	4280	4298	4316	4334	9	5.00
2400	4352	4370	4388	4406	4424	4442	4460	4478	4496	4514	10	5.56
2500	4532	4550	4568	4586	4604	4622	4640	4658	4676	4694	11	6.11
2600	4712	4730	4748	4766	4784	4802	4820	4838	4856	4874	12	6.67
2700	4892	4910	4928	4946	4964	4982	5000	5018	5036	5054	13	7.22
2800	5072	5090	5108	5126	5144	5162	5180	5198	5216	5234	14	7.78
2900	5252	5270	5288	5306	5324	5342	5360	5378	5396	5414	15	8.33
3000	5432	5450	5468	5486	5504	5522	5540	5558	5576	5594	16	8.89
3100	5612	5630	5648	5666	5684	5702	5720	5738	5756	5774	17	9.44
3200	5792	5810	5828	5846	5864	5882	5900	5918	5936	5954	18	10.00
3300	5972	5990	6008	6026	6044	6062	6080	6098	6116	6134		
3400	6152	6170	6188	6206	6224	6242	6260	6278	6296	6314		
3500	6332	6350	6368	6386	6404	6422	6440	6458	6476	6494		
3600	6512	6530	6548	6566	6584	6602	6620	6638	6656	6674		
3700	6692	6710	6728	6746	6764	6782	6800	6818	6836	6854		
3800	6872	6890	6908	6926	6944	6962	6980	6998	7016	7034		
3900	7052	7070	7088	7106	7124	7142	7160	7178	7196	7214		
C. °	0	10	20	30	40	50	60	70	80	90		

EXAMPLES: 1347° C. 2444° F. +12°.6 F. = 2456°.6 F.: 3367° F. = 1850° C. +2°.78 C. = 1852°.78 C.



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